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## INTRODUCTION

Stress fractures can be extremely costly to the military in terms of both time and medical expenses. The tibia is a common site for such injuries and has been most often associated with running, an activity common to all military training. Stress fractures are among the top 5 cited lower extremity injuries sustained by runners (Clement et al., 1981; Kowal, 1980; James et al., 1978; Jones, 1983; Pagliano and Jackson, 1980; Reinker and Ozburne, 1979). They are among the most serious of running-related overuse injuries as they take long to heal and if untreated, can progress to a macrofracture. Females are a growing military contingency and appear to be particularly susceptible, as it has been noted that they are twice as likely to experience a stress fracture as their male counterparts (Brudvig et al, 1983; Pester and Smith, 1992; Reinker and Ozburne, 1979).

Structural and biomechanical factors have been suggested in the cause of stress fractures. However, these mechanisms are not well understood. Therefore, the purposes of this study are 1) to compare the structure and mechanics of runners who have sustained a tibial stress fracture to those who have not, 2) to gain an understanding of which combination of factors (structural and/or biomechanical) are predictive of tibial stress fractures, and 3) to assess whether mechanics are altered following a tibial stress fracture. Once the factors associated with stress fractures are identified, future work will focus on formation and testing of a simple screening tool to facilitate identification of those at risk.

This is a dual-site investigation (University of Delaware & University of Massachusetts, Amherst) which began on September 1, 2000 and has been under investigation for four years. This Annual Report will focus on intermediate results after the fourth year of the study.

## BODY

### Summary of Methodology

The overall aim of this research is to gain insight into the etiology of tibial stress fractures. Three dimensional motion analysis data along with structural data will be collected from 400 subjects (200 at each site) over a 3-year period. A minimum of 30 subjects will have sustained a tibial stress fracture prior to the study. Subjects will be recruited primarily from track teams, running clubs, and physicians local to the University of Delaware and University of Massachusetts. All subjects will be females between the ages of 18 and 45 and will be free of lower extremity injury at the time of testing. Lower extremity kinematics and kinetics will be collected during running. In addition, radiographs of both tibiae will be taken as well as clinical measures of lower extremity alignment. Subjects will then report their exposure data (mileage, intensity, terrain) as well as any injuries they have sustained each month via a custom developed webpage which will serve as a database for this information. If a subject reports a tibial stress fracture/reaction, the site coordinator will be notified automatically and the subject

will be asked to return for a second running analysis once the fracture has healed and they are cleared to run by their physician. The structural and biomechanical factors leading up to a tibial stress fracture will be assessed. In addition, comparisons will be made of mechanics before and after the stress fracture to determine whether subjects revert to their pre-injury mechanics. If relationships between mechanics and injury are established, future interventions including gait retraining should be explored.

### **Statement of Work**

Between the two data collection sites, the following objectives were outlined in the approved Statement of Work for the fourth year. These objectives included:

1. Recruit any additional subjects needed, collect and reduce their data and continue with follow-ups.
2. Complete initial data analysis once groups are complete
3. Data will be recollected on any subjects who have sustained a fracture
4. Preliminary predictive models attempted based on the data of subjects who have fractured during the course of the study to date
5. Abstract submitted to the American Society of Biomechanics Meeting regarding predictive model of tibial stress fractures
6. Continue with follow-up procedures on subjects.

### **Adherence to Work Objectives**

#### **1) Recruitment of Subjects**

To date, data have been collected on a total of 396 subjects: 206 at the University of Delaware and 190 at the University of Massachusetts. In the last year, 44 subjects have been collected in Delaware and 75 in Massachusetts. The target for the year was 38 at the University of Delaware and 85 at the University of Massachusetts, to complete the recruitment of 400 runners. Slightly more than the target have been recruited at the University of Delaware. This was to reduce the burden on University of Massachusetts this year.

Clearly, the measures we put in place to improve recruitment, were successful. Specifically, we targeted the influx of new student athletes at the beginning of the Fall semester is an excellent opportunity to recruit large numbers of subjects in a short period of time. Over the last three years, good relationships have been established and maintained with women's cross country and track coach working with University teams. In addition, several local road races that took place in the Fall were identified and attended. A booth at these events has proven to be an effective recruitment tool. We also continued to advertise the study on notice boards in local running shops and around campus (see Appendix 2 for flyer). According to the Statement of Work, all 400 subjects would be recruited by the third anniversary of the project. However, due to a delay in website development at the outset of the study, data collection did not get underway until September 1 2000. As a result of these delays in year one, and low levels of recruitment

in the early years, we are just now completing the recruitment of 400 subjects at the end of year 4.

As with all prospective studies, the exact number of injuries that will occur in the study sample is unknown. The reported incidence of stress fractures ranges from 1-25% (Bensel et al., 1983; Brudvig et al., 1983; Kowal, 1980; McBryde et al., 1981; Milgrom et al., 1989; Reinker et al., 1979; Zernicke et al., 1993). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (Pester & Smith, 1992). We based our power calculations on a 5% incidence rate. Therefore, given 400 subjects, we expected 20 fractures. To date, we only have 4 prospective tibial stress fractures. We believe this to be due, in part, to the nature of our sample. Our original age inclusion criteria was between 18-45 yrs, and we had inadvertently recruited a fairly large sample of women between the ages of 35-45. However, there is evidence that suggests younger runners (18-30) experience stress fractures at a higher rate than their older counterparts. Therefore, we have narrowed our inclusion criteria to women between the ages of 18-30 to fill out this age group. This has reduced the proportion of runners over aged 35 recruited from 43% at the time of last year's report to 27% now. Additionally, we have increased our minimum mileage requirements from 20 miles per week to 30 miles per week. Higher mileages are more likely to precipitate injuries from biomechanical abnormalities, due to the repetitive nature of running.

We believe these measures will assist us in capturing more tibial stress fractures. To facilitate this, we would like to extend the recruitment and data collection period by an additional year. In order to follow-up with these subjects for a minimum of one year, we would need to request a one year, no cost extension. We believe this will provide us with additional subjects to increase the power of the study.

## **2) Completion of initial data analysis of two groups of subjects (those with and without a history of tibial stress fracture)**

The initial data analysis comparing a group of runners with a history of tibial stress fracture to an age- and mileage-matched control group without any previous lower extremity stress fractures has been completed. A draft version of this manuscript is included in Appendix 1. The results of this analysis are reported in the Reportable Outcomes section of this report.

## **3) Collection of Data on those who have sustained a stress fracture**

To date, four tibial stress fractures have been recorded prospectively. To date, 3 of these have now returned to the laboratory for a post-injury gait reassessment. The data from these individuals are presented in the Reportable Outcomes section as case studies. In addition, we have included data from 5 other subjects (non-tibial lower extremity stress fractures and a tibial stress reaction) who have returned to the laboratory for post-injury reassessment. These data provide an initial indication of whether there are changes in running mechanics following recovery from a tibial stress fracture.

The data from the tibial stress fracture group prospectively are also included in the Reportable Outcomes section in a comparison with a matched control group of subjects who have not sustained a fracture. Due to the low number of tibial stress fractures or reactions that have occurred during the study so far, we have also included a comparison of all subjects who have sustained a lower extremity stress fracture (pelvis and distally) to a matched control group.

To date, 31 subjects with 41 fractures have entered the study with a history of previous tibial stress fracture. The results of the initial comparison of these data with matched subjects who do not have a history of tibial stress fracture are presented in the Reportable Outcomes section. These results form the basis of a manuscript about the lower extremity mechanics of female runners after tibial stress fracture that is near ready for submission for publication.

There have been minor losses of data due to problems encountered during data collection or reduction. For example, of the 31 subjects with a history of tibial stress fracture, 2 could not remember which side the injury was on, so data for their injured side could not be included for further analysis. Additionally, five subjects were found to be midfoot or forefoot strikers during further data analysis, and so excluded from our comparisons. Our comparisons are made between groups of rearfoot strikers (representing the foot strike pattern of the majority of the running population), to reduce the within-group variability. Data for 24 stress fracture subjects plus 24 age and mileage matched controls were processed.

#### **4) Preliminary predictive models attempted based on the data of subjects who have fractured during the course of the study to date**

Due to the lower than expected occurrence of tibial stress fractures while subjects are enrolled in the study, we are unable to develop any preliminary predictive models at this stage. We hope that by focusing our recruitment efforts on young, high mileage runners, we will have a higher incidence of prospective stress fractures over the next 12 months. If this measure does not yield enough tibial stress fractures, we will develop the predictive equation based on all prospective stress fractures.

#### **5) Abstract and manuscript submission**

##### **Manuscript Submission**

Two articles are in final preparation for submission to peer-reviewed journals for publication. The first of these is titled "Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners" and will be submitted to *Medicine and Science in Sport and Exercise* in the next month. The second article is being developed from an abstract presented at the American College of Sports Medicine National Meeting in 2003 and is titled "Prospective Biomechanical Investigation of Iliotibial Band Syndrome in Competitive Female Runners". It will be submitted to *Medicine and Science in Sport and Exercise* in the next month as well. Draft versions of both articles are included in

Appendix 1. While we had hoped to submit these articles by the end of last year, the submissions were postponed to enable a greater number of injured subjects to be included in our analysis. Finally, we are in the process of preparing an additional manuscript on "The Relationship between the Free Moment of the Vertical Ground Reaction Force and Tibial Stress Fractures" that will be submitted to the Journal of Biomechanics by the end of 2004. A number of other manuscripts are planned for the next year addressing the prospective stress fractures as well as other injuries including plantar fasciitis and patellofemoral pain syndrome

#### **Abstract Submission**

In the past year, six additional abstracts have been submitted and were accepted for presentation. Three abstracts were presented at the American College of Sports Medicine National Meeting in Indianapolis, Indiana and three will be presented at the American Society of Biomechanics Annual Meeting in Portland, Oregon in September 2004. The references are provided in the Reportable Outcomes section and the complete abstracts are included in Appendix A. In addition, two abstracts were presented at the Center for Biomedical Engineering Research Symposium held at the University of Delaware.

#### **6) Follow-up procedures**

Subjects have been tracking their monthly running exposure and injuries since their initial visit and these data have been input into the database. The database continues to function properly and subjects have been logging in on a monthly basis to record their mileage and injuries. A summary of the injuries reported has been summarized in the Reportable Outcomes section.

Seventy-two subjects have now completed their participation in the study, including two year follow up. Fifty subjects from the University of Delaware have completed, and 22 at the University of Massachusetts. These relatively low numbers reflect the slow rate of recruitment at the beginning of the project, and do not include any participants that have withdrawn or dropped out of the study.

The compliance rate for the follow up part of the study is high, and stands currently at 86%, an improvement on the 80% compliance rate reported last year. This is a positive result, since more subjects have now been enrolled in the study for a longer time, providing greater opportunity for attrition. A dropout was defined as a subject not having entered a monthly report into the website for 12 or more consecutive months. Subjects who have not responded to the monthly email request for their running data for a shorter period are contacted by telephone to obtain backdated monthly information. This method seems to have been successful. To date, a total of 57 subjects have dropped out of the study. In addition, 10 subjects that have stopped running for various reasons have withdrawn from the study. This has resulted in an overall attrition rate of 17%. This is low for a follow up study of this long duration with such a large number of subjects enrolled, and is not a cause for concern.



Currently, compliance rate is calculated as the number of monthly responses submitted by a subject being divided by the number of monthly requests for data. Additional entries that were received from some of the early recruits to the project, backdating their records to the months before the website was online, are not included. Furthermore, any erroneous double submissions of the same data were excluded from the total number of submitted entries for an individual. It was felt that this rigorous method provides the best indication of compliance rate during follow up.

Previously, the reviewers of the Annual Report have suggested that the self-report injury information collection forms on the website may contain items that are hard for the participants to judge due to anatomical and medical terms being used. If self diagnosed initially, subjects are encouraged to report their injuries after they have been diagnosed by a medical professional. To date, only 104 of 747 (14%) of prospective injuries reported to date were diagnosed or treated by someone other than a medical professional. This is an improvement on last year when 53 of 226 (23%) prospective injuries reported to date were diagnosed or treated by someone other than a medical professional. We believe this improvement is due to following up self-reported injuries by email to determine whether a medical professional was consulted at any time for the injury, and to diagnose the injury following discussion with the subject, if possible.

Subjects are encouraged to contact us if there is a question regarding their injury. They are also provided a space for comment on the online form regarding their injury. When any injuries related to the anterior lower leg are reported a clinician on the project will follow up with a telephone call. Therefore, we are able to further confirm the diagnosis. Any reported tibial stress fractures must be confirmed by x-rays, bone scans or MRIs. Tibial stress reactions have been operationally defined as bony pain specifically along the distribution of the tibia that is worsened with impact loading and relieved with rest. There is indication in the literature (Fredericson et al., 1995) that these stress reactions are the early stage of a stress fracture.

## KEY RESEARCH ACCOMPLISHMENTS

The main focus of this study is the elucidation of the relationships between lower extremity structure, mechanics and the occurrence of tibial stress fractures. However, the large database of biomechanical, training and injury data that is being compiled during the study is proving to be a valuable source of retrospective and prospective information relating to other running injuries. To date, seven abstracts that have been presented at various national and international conferences about the incidence of lower extremity stress fractures and their relationship to kinematic, kinetic and structural variables, the main thrust of the study. Additionally, a further six abstracts concerning the relationships between lower extremity mechanics and three common running injuries: iliotibial band friction syndrome, plantar fasciitis and patellofemoral pain syndrome have been presented. One article is in final preparation for submission to a peer-reviewed journal about the relationship between history of tibial stress fracture and differences in kinematic, kinetic and structural variables. A second article is in final preparation for submission to a peer-reviewed journal about the relationship between history of iliotibial band syndrome and differences in kinematic, kinetic and structural variables.

At completion, the database generated from the 400 runners enrolled into this study will be a very comprehensive record of the biomechanics of female runners, their injury history and prospective injuries over a two year period. This will prove to be an invaluable resource not only in relation to stress fractures, but the many other running injuries that are common and result in time lost from training for both civilians and military recruits.

## REPORTABLE OUTCOMES

This section contains all of the Reportable Outcomes to date:

- 1) Retrospective tibial stress fracture data for the manuscript that is in preparation for submission by the end of 2004
- 2) A summary of the prospective tibial stress fracture and tibial stress reaction data
- 3) A summary of all the lower extremity prospective stress fracture data
- 4) A summary of the pre and post injury data from the four prospective tibial stress fractures/ syndromes that have returned for a second assessment following recover from injury
- 5) Details of the abstracts presented based on data collected during this study
- 6) Other presentations made
- 7) A summary of the information recorded in the database.
- 8) A summary of degrees obtained that are supported by this award
- 9) A summary of employment and research opportunities applied for and received based on experience and training supported by this award

### **1) Summary of data on female runners who had sustained a tibial stress fracture previously**

Aim 1: Determine whether differences in structure and mechanics exist between subjects with a prior tibial stress fracture to those who have not sustained a fracture.

At present, we have data for retrospective tibial stress fractures have been reported in 24 subjects. This group (RTSF) was matched with 24 control subjects (CON), who have never sustained any stress fractures, to enable assessment of the lower extremity structural and functional differences between the two groups. The groups were matched for monthly running mileage and age, to remove the influence of these potentially confounding factors (Table 1).

Table 1: Mean ( $\pm$  standard deviation) monthly running mileage and age of the TSF and CON groups

	<b>Mileage (miles/ month)</b>	<b>Age (years)</b>
TSF (n=24)	121 $\pm$ 46	29 $\pm$ 11
CON (n=24)	119 $\pm$ 47	26 $\pm$ 9

Ground reaction force (GRF), kinematic data, and tibial acceleration data were recorded and averaged from 5 running trials. Radiographs of the distal lower extremity were used to calculate the tibial area moment of inertia (Milgrom et al., 1989). Each subject underwent a structural evaluation by an experienced physical therapist.

**Hypothesis 1.1: Runners who had sustained a previous TSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.**

Subjects who had sustained a tibial stress fracture previously exhibited significantly greater instantaneous and average vertical loading rates (Figs. 1 and 2). No differences in impact peak, peak vertical and braking forces or leg stiffness were observed between the two groups (Table 2). However, an increase in the average loading rate during braking was found in the RTSF group (Fig. 3). This lack of difference in ground reaction force peaks between RTSF and CON groups has been reported previously (Crossley et al., 1999; Bennell et al., 2004), although one group has reported increases in these peak values in RTSF groups. These existing studies did not consider loading rates in their comparisons; loading rates have consistently shown differences between RTSF and CON groups in our comparisons.

Average and instantaneous loading rates during braking have not been reported on in previous years. However, this secondary component of the ground reaction force peaks at approximately 50% of body weight and represents a substantial load to the lower extremity during the stance phase of running. It may be that differences here, multiplied over the 1000's of steps made by the distance runner, make a significant contribution to injury risk. As loading rates in the vertical direction have been increased in subjects with stress fractures, we decided to investigate loading rates during braking, in addition to peak braking force in the anteroposterior direction. Similarly, vertical impact peak was included to see if this initial peak during loading was related to the occurrence of tibial stress fracture.

Additionally, individual joint stiffness, the change in joint angle over change in joint moment, was also investigated for the first time this year. Thus far, the global measure of leg stiffness during the first half of stance has not appeared to be related to the incidence of tibial stress fracture. Therefore, we chose to investigate the individual knee and ankle stiffness in the sagittal plane. We evaluated this stiffness over the period from foot strike to peak knee flexion, i.e. during loading of the lower extremity. Subjects with a history of tibial stress fracture had significantly higher knee joint stiffness than the control group (Fig. 4), but no difference was observed at the ankle. A stiffer knee may result in less shock attenuation by the lower extremity, thereby increasing the risk of stress related injuries.

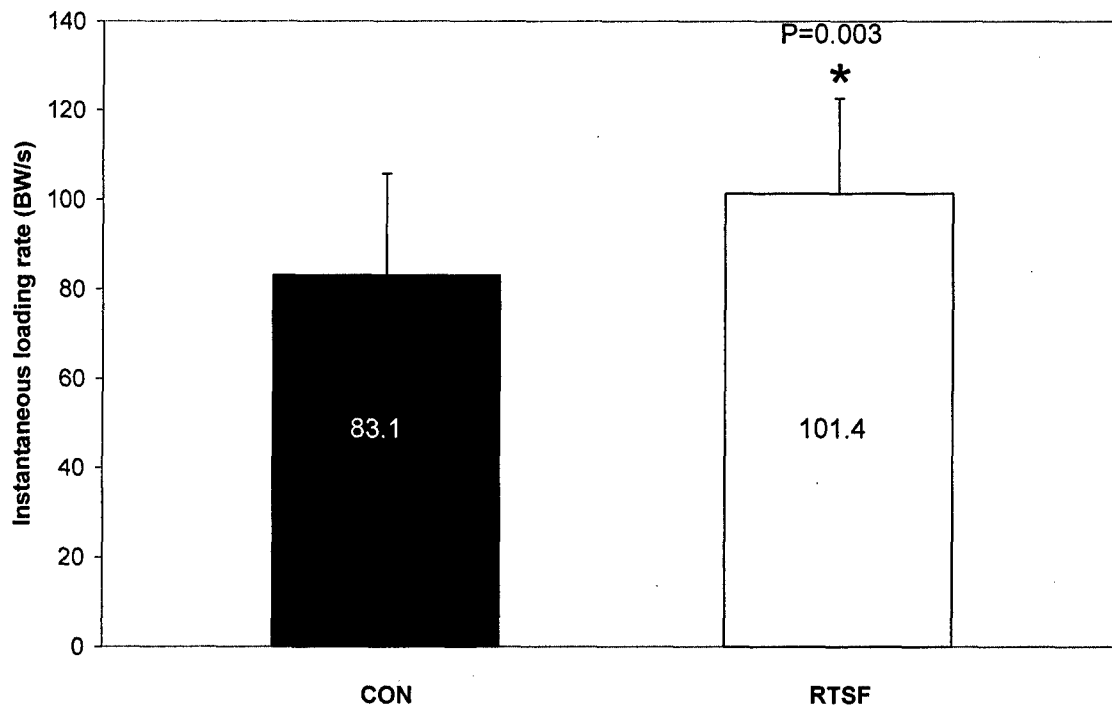


Figure 1: Instantaneous loading rate in subjects who had a previous tibial stress fracture versus healthy controls (\* = significantly greater than controls).

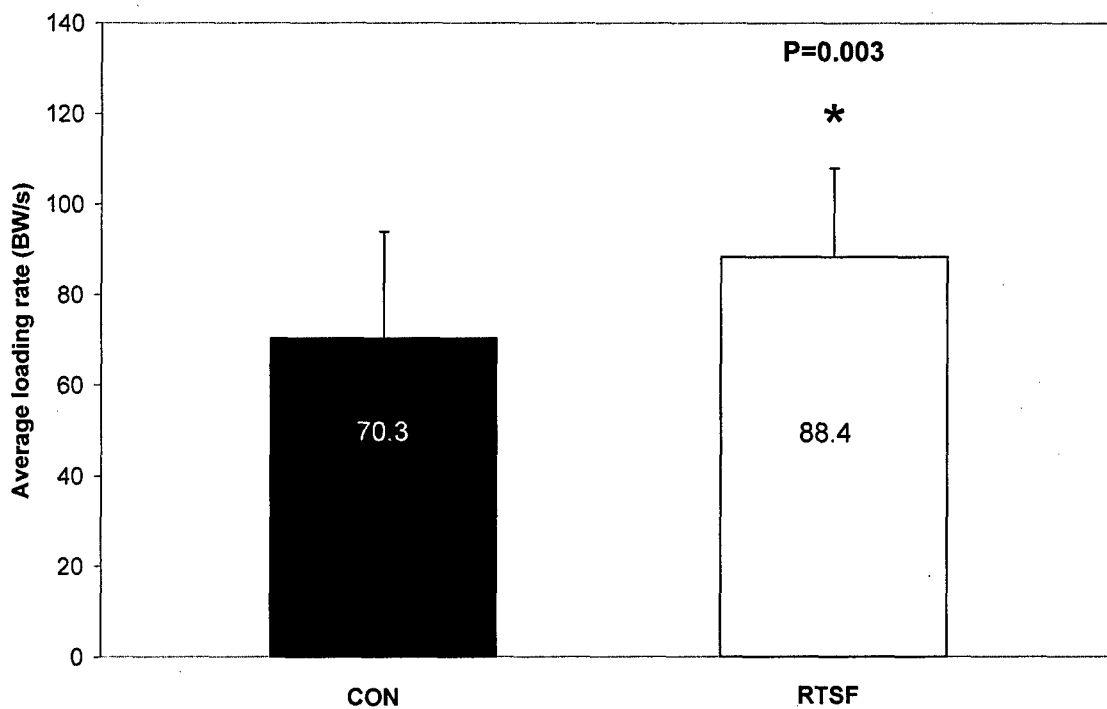


Figure 2: Average vertical loading rate in subjects who had a previous tibial stress fracture versus healthy controls (\* = significantly greater than controls).

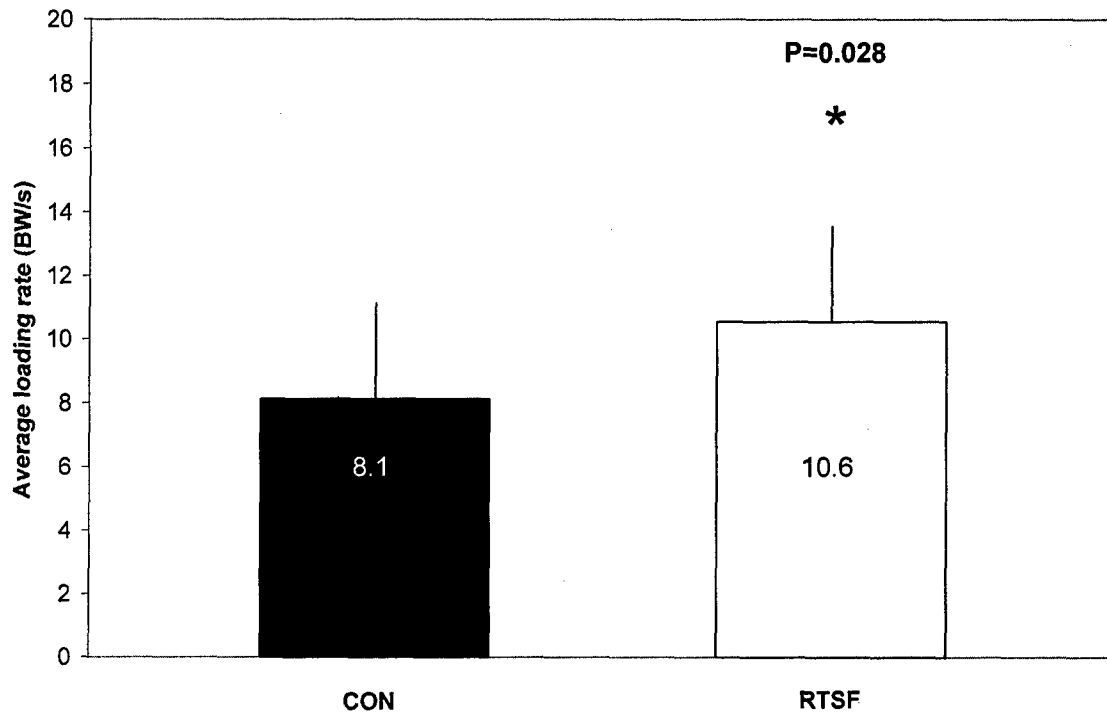


Figure 3: Average anteroposterior loading rate in subjects who had a previous tibial stress fracture versus healthy controls (\* = significantly greater than controls).

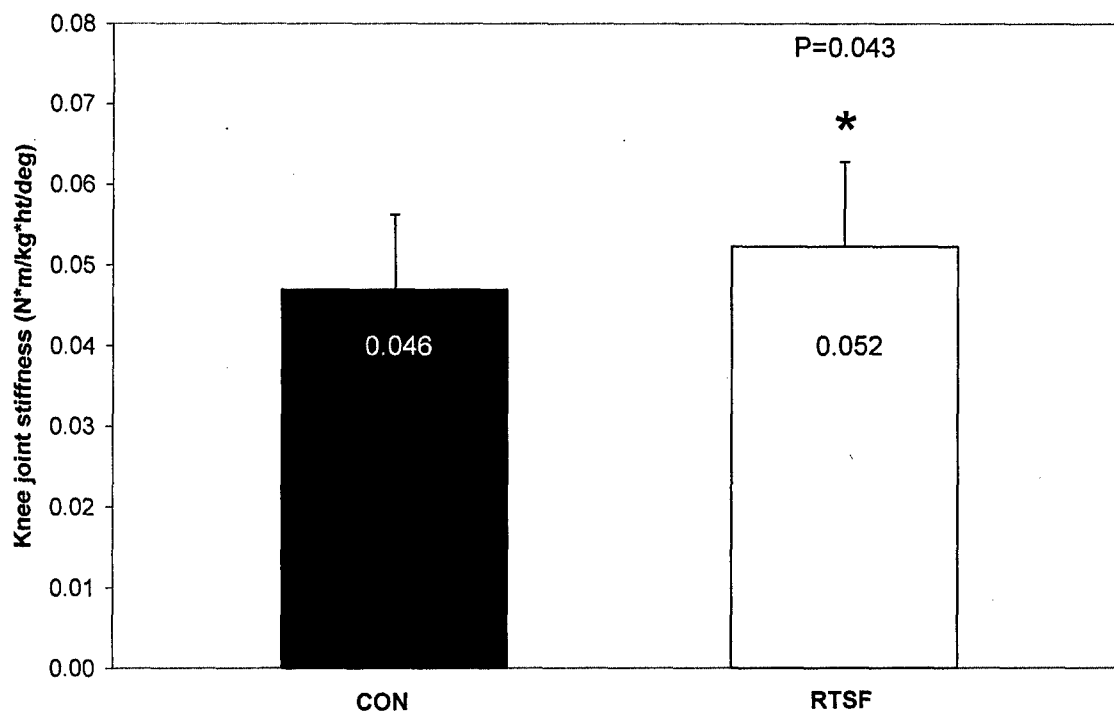


Figure 4: Average sagittal plane knee joint stiffness in subjects who had a previous tibial stress fracture versus healthy controls (\* = significantly greater than controls).

**Hypothesis 1.2: Runners who had sustained a previous TSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.**

Subjects who had sustained a previous tibial stress fracture exhibited significantly greater peak positive tibial acceleration than control subjects.. There was no difference in ankle dorsiflexion excursion between the two groups. Knee joint excursion was reduced in the TSF group, and this change was reflected in an increase in knee joint stiffness in these runners. A “stiff” runner will spend less time in contact with the ground (Farley and Gonzalez, 1996) and will attenuate less shock between the leg and the head (McMahon et al., 1987). This is in agreement with the findings of Farley and Gonzalez (1996) who suggested lower extremity stiffness and knee flexion excursion are highly correlated and may lead to stress fracture.

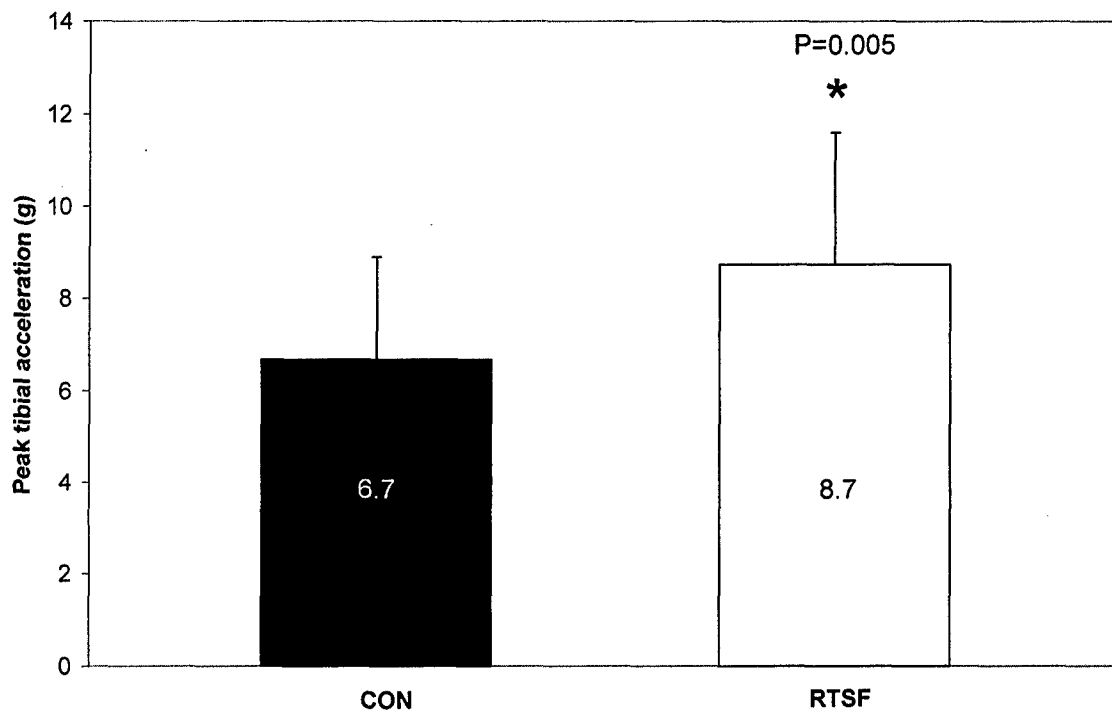


Figure 5: Peak positive tibial acceleration in subjects who had a previous tibial stress fracture versus healthy controls (\* = significantly greater than controls).

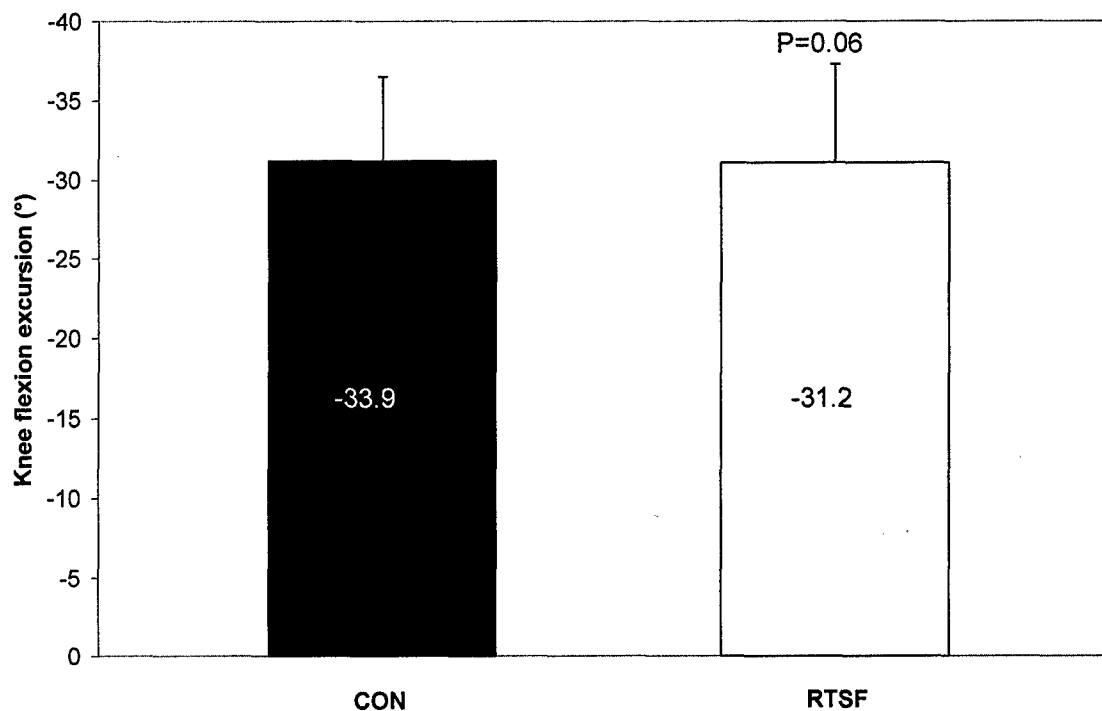


Figure 6: Knee flexion excursion in subjects who had a previous tibial stress fracture versus healthy controls (\* = significantly less than controls).

**Hypothesis 1.3: Runners who had sustained a previous TSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.**

Although specific structural characteristics have been associated with stress fracture injuries in male runners (Crossley et al., 1999; Milgrom et al., 1989), these groups of female distance runners did not demonstrate this relationship. No difference in tibial area moment of inertia or tibial varum was observed between the two groups (Table 2). These data are in agreement with recent work by Bennell et al. (2004), who found no difference in tibial bone geometry between female runners with and without a history of tibial stress fracture.



Table 2: Variables that showed no difference between subjects who had a previous tibial stress fracture and healthy controls.

	<b>RTSF</b>	<b>CON</b>	<b>P value</b>
Ankle dorsiflexion excursion	20.60 ± 5.48	22.09 ± 4.07	0.15
Peak vertical force (BW)	2.51 ± 0.19	2.53 ± 0.15	0.34
Impact peak (BW)	1.85 ± 0.19	1.77 ± 0.34	0.15
Peak braking force (BW)	-0.40 ± 0.07	-0.39 ± 0.05	0.34
Instantaneous braking load rate (BW/s)	21.93 ± 7.29	20.95 ± 5.36	0.30
Leg stiffness (kN/m)	8.78 ± 1.55	9.07 ± 1.49	0.28
Ankle jt stiffness (Nm/mass*ht <sup>o</sup> )	0.33 ± 0.35	0.29 ± 0.38	0.36
Area moment of inertia (mm <sup>4</sup> )	11403 ± 3224	12507 ± 3813	0.20
Tibial varum (°)	5.71 ± 2.31	6.43 ± 1.59	0.11

The observed decreases in knee joint excursion suggest that stiffness would be increased in the RTSF group. This was supported by the measure of knee joint stiffness that was included in this analysis, but not by the global measure of vertical leg stiffness. It appears that the stiffness of the individual joints, may be a more sensitive measure than the simple global measure employed initially. The observed increases in vertical loading rate and tibial acceleration support the notion that these impact-related kinetic variables may be related to the risk of tibial stress fracture. Additionally, the increase in average loading rate during braking suggests that this secondary plane may be of some importance in relation to tibial stress fracture.

There were no differences in tibial area moment of inertia between the RTSF and control groups. This is contrary to the study by Milgrom et al. (1989) who found a highly significant reduction in tibial area moment of inertia in the recruits who sustained a tibial stress fracture. However, they studied male military recruits compared to female runners examined in our study. The lack of a significant difference between the RTSF and control groups in this preliminary analysis suggests that other factors may be important in the etiology of tibial stress fractures in the female running population. Overall, area moment of inertia values in the RTSF group were 20% less than those reported by Milgrom et al. (1989). However, this is due to the smaller tibial width of females, which is correlated strongly with tibial area moment of inertia. Furthermore, the recent work by Bennell et al. (2004) suggests that these structural differences are not present in groups of female runners with and without a history of tibial stress fracture.

It should be noted that the kinetic differences between the RTSF and control groups are similar to those reported for the smaller group (n=20) of subjects that was considered last year. This year, our understanding of the differences between the groups has been enhanced by the inclusion of several extra stiffness and ground reaction force variables. These variables were included based on trends that we have observed in the data over the past year.

## **2) Summary of the prospective data obtained on female runners who sustained a tibial stress fracture or tibial stress reaction during the study**

Aim 2: Determine whether differences in structure and mechanics exist between subjects who sustain a tibial stress fracture or reaction (PTSF) to those who do not sustain a fracture.

Currently, only a relatively small number of participants have experienced tibial stress fractures (n=4) or tibial stress reactions (n=4) during the follow-up period of the study. Due to the small number of participants who have experienced a tibial stress fracture, those that have experienced a tibial stress reaction (TSR) are also included in this analysis. Since TSR has been shown to be the precursor of TSF, we felt it was appropriate to include these. A participant in the study who manages her injuries promptly and appropriately is less likely to experience the progression from TSR to TSF. Therefore inclusion of the TSR group enables the mechanics of susceptible individuals to be determined and compared to healthy controls. The PTSF group was compared to an age and mileage-matched control group (Table 3).

Table 3: Mean ( $\pm$  standard deviation) monthly running mileage and age of the PTSF and CON groups

	<b>Mileage (miles/ month)</b>	<b>Age (years)</b>
PTSF (n=8)	86 $\pm$ 40	22 $\pm$ 4
CON (n=8)	90 $\pm$ 35	22 $\pm$ 4

**Hypothesis 2.1: Runners who sustained a TSF or TSR would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.**

Due to the small number of subjects in each group, statistical analyses of these data were not conducted. Instead, we have operationally defined a difference of 15% between the groups as indicating a clinically significant difference. However, those subjects who sustained a tibial stress fracture (or reaction) during the study did not show many differences from the control group. Only one loading variable was different from the matched control group: instantaneous loading rate during braking (Fig. 7). However, this was 26% smaller than the control group, the opposite of our hypothesis. These preliminary results from the TSFs sustained during the study should be interpreted cautiously, since the number of subjects involved is small.

Greater differences were noted in last year's report. However, since the control group is matched for age and mileage, the characteristics of the control group are different this year. Generally, the control group included here has higher ground reaction force and shock values than the 2003 control group. For example, the shock values were 4.73g for the control group last year and 6.48 g this year. Due to the small number of subjects

involved, these data are sensitive to the specific subjects sampled and can change noticeably with the addition or exclusion of even one individual's data. We aim to address this lack of power in our prospective comparisons by focusing additional data collections on a targeted 'high-risk' group.

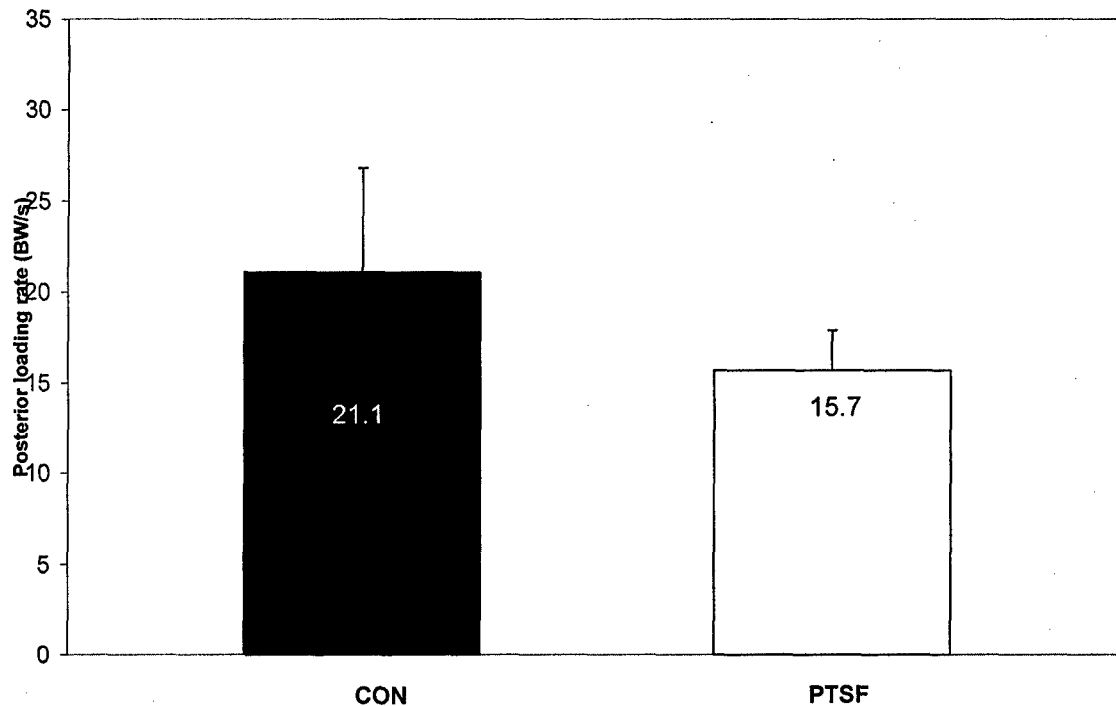


Figure 7: Instantaneous loading rate during braking in subjects who developed a tibial stress fracture (or syndrome) versus healthy controls.

**Hypothesis 2.2: Runners who sustained a PTSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.**

No differences in kinematic characteristics or tibial acceleration were found between the prospective TSF group and the healthy controls (Table 4). This differs from the retrospective TSF group, which had reduced knee flexion excursion and tibial acceleration compared to the control group. Although the group mean values were similar, there were some individuals within the PTSF group who had excessively high values. For example, two PTSF subjects had tibial shock value over 9g, higher than the mean value for the RTSF group. These same two subjects also had instantaneous vertical loading rates over 100 BW/s, also higher than the average of the RTSF group.

**Hypothesis 2.3: Runners who sustained a PTSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.**

Tibial varum was unexpectedly reduced (by 19%) in the prospective TSF group compared to the healthy controls (Fig. 8).

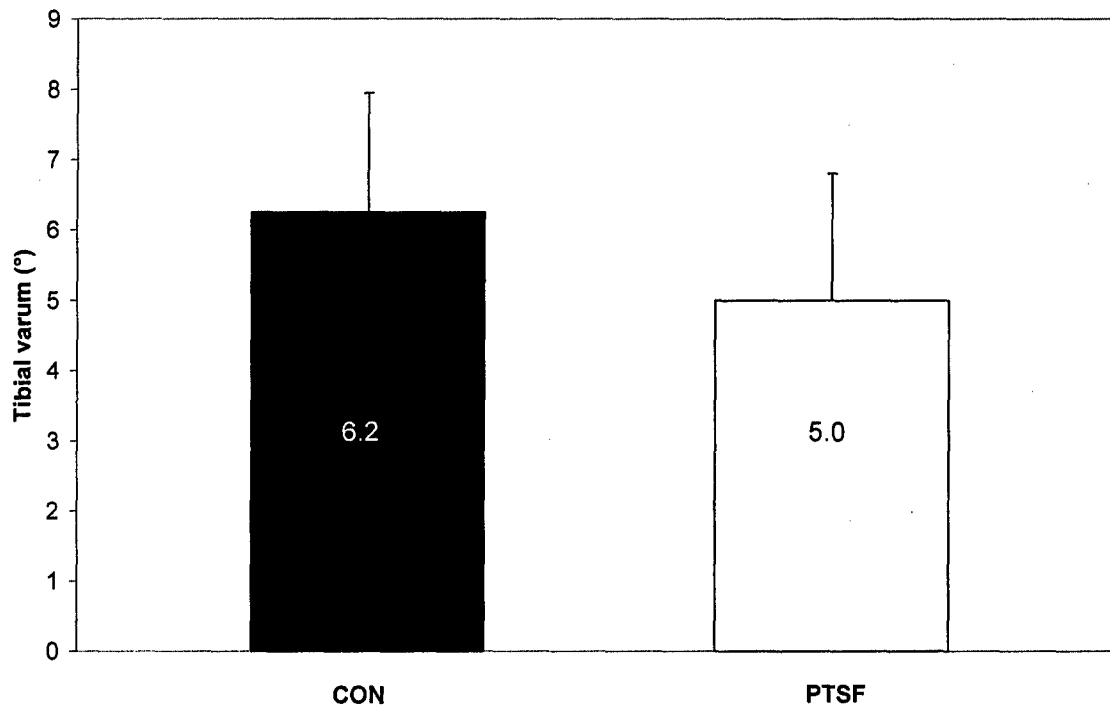


Figure 8: Tibial varum in subjects who developed a tibial stress fracture (or syndrome) versus healthy controls.

Table 4: Variables that showed no difference between subjects who had a previous tibial stress fracture and healthy controls.

	PTSF	CON	% diff.
Impact peak (BW)	1.81 ± 0.24	1.88 ± 0.38	-3.6
Peak vertical force (BW)	2.44 ± 0.14	2.57 ± 0.6	-5.1
Vertical instantaneous load rate (BW/s)	84.55 ± 26.21	78.11 ± 20.41	8.2
Vertical average load rate (BW/s)	71.43 ± 26.40	65.95 ± 23.07	8.3
Peak braking force (BW)	-0.34 ± 0.05	-0.39 ± 0.06	-14.0
Braking average load rate (BW/s)	8.36 ± 3.14	9.01 ± 4.26	-7.3
Peak positive tibial acceleration (g)	6.49 ± 2.43	6.48 ± 0.76	0.1
Vertical leg stiffness (kN/m)	8.70 ± 0.68	8.85 ± 1.47	-1.7
Ankle joint stiffness (Nm/mass*ht <sup>0</sup> )	0.35 ± 0.26	0.36 ± 0.39	-4.4
Knee joint stiffness (Nm/mass*ht <sup>0</sup> )	0.04 ± 0.01	0.04 ± 0.01	4.2
Ankle dorsiflexion excursion (°)	20.54 ± 2.57	21.37 ± 5.41	-3.9
Knee flexion excursion (°)	-33.82 ± 3.68	-35.10 ± 4.51	-3.7
Area moment of inertia (mm <sup>4</sup> )	11634 ± 1214	11244 ± 3343	3.5

In conclusion, the limited amount of data so far available for prospective tibial stress fractures and tibial stress reactions does not reflect differences observed in the retrospective tibial stress fracture group. Minor differences were found in ground reaction force and structural variables. This may partly be a consequence of the small subject group. Furthermore, we included confirmed tibial stress syndrome in this group to double subject numbers, and so increase the power of the sample to detect differences. Inclusion of this group may have influenced the outcome. By concentrating our final recruitment on high risk groups, we hope to have more occurrences of prospective tibial stress fracture in the next 12 month period. This will enable us to compare a more homogeneous group to uninjured controls, to try and elucidate pre-existing differences between runners who sustain a tibial stress fracture and those who do not.

### **3) Summary of the prospective data obtained on ALL of the lower extremity stress fractures: comparison to uninjured female runners**

Aim 3: Determine whether differences in structure and mechanics exist between subjects who sustain a tibial stress fracture or reaction (PTSF) to those who do not sustain a fracture.

Due to the small number of participants who have experienced a TSF, we also analyzed all prospective stress fracture injuries combined (4 TSF, 4 femoral, 1 pelvic, 2 fibular, 4 metatarsal).

Table 5: Mean ( $\pm$  standard deviation) monthly running mileage and age of the PSF and CON groups

	<b>Mileage (miles/ month)</b>	<b>Age (years)</b>
PSF (n=15)	99 $\pm$ 39	27 $\pm$ 11
CON (n=15)	102 $\pm$ 26	28 $\pm$ 11

**Hypothesis 3.1: Runners who sustained a PSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.**

While not yet statistically significant, subjects who sustained a PSF during the study exhibited a clinically significant ( $\geq 15\%$ ) increase in instantaneous (16%) and average (15%) vertical loading rates (Fig. 9 & 10). This was consistent with the findings of the subjects who had previously sustained a TSF. No difference in leg stiffness or joint stiffness was found between the PSF group and the healthy controls (Table 6). Also, there were no differences in the anteroposterior ground reaction force variables.

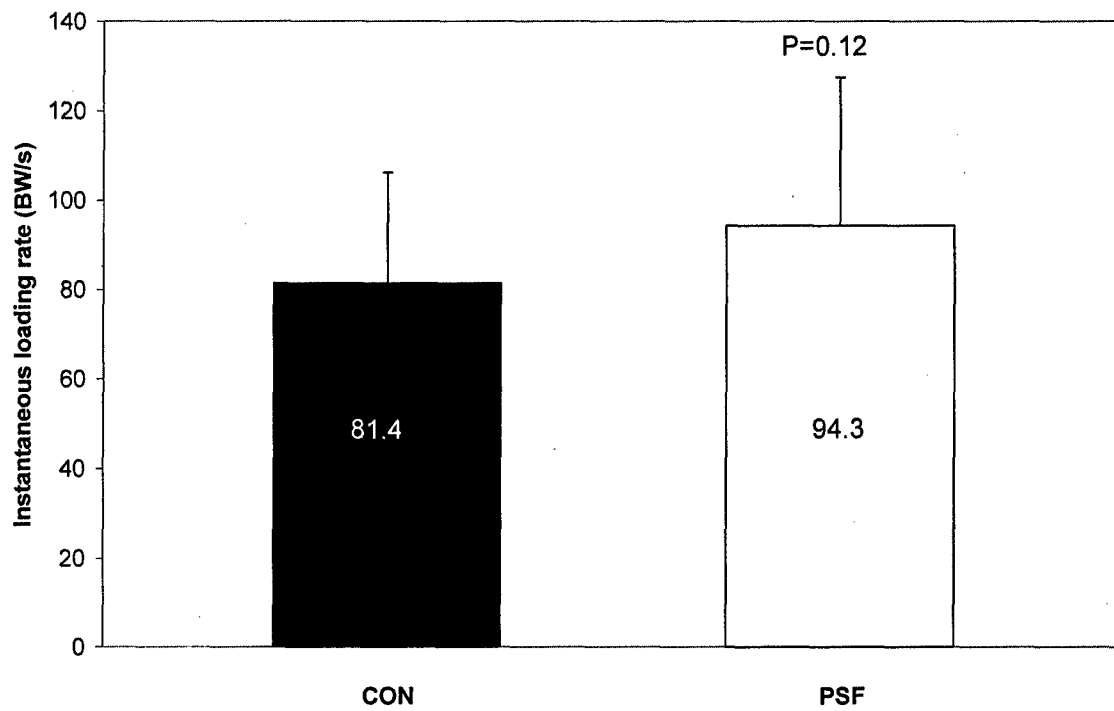


Figure 9: Instantaneous loading rate in subjects who developed a stress fracture versus healthy controls.

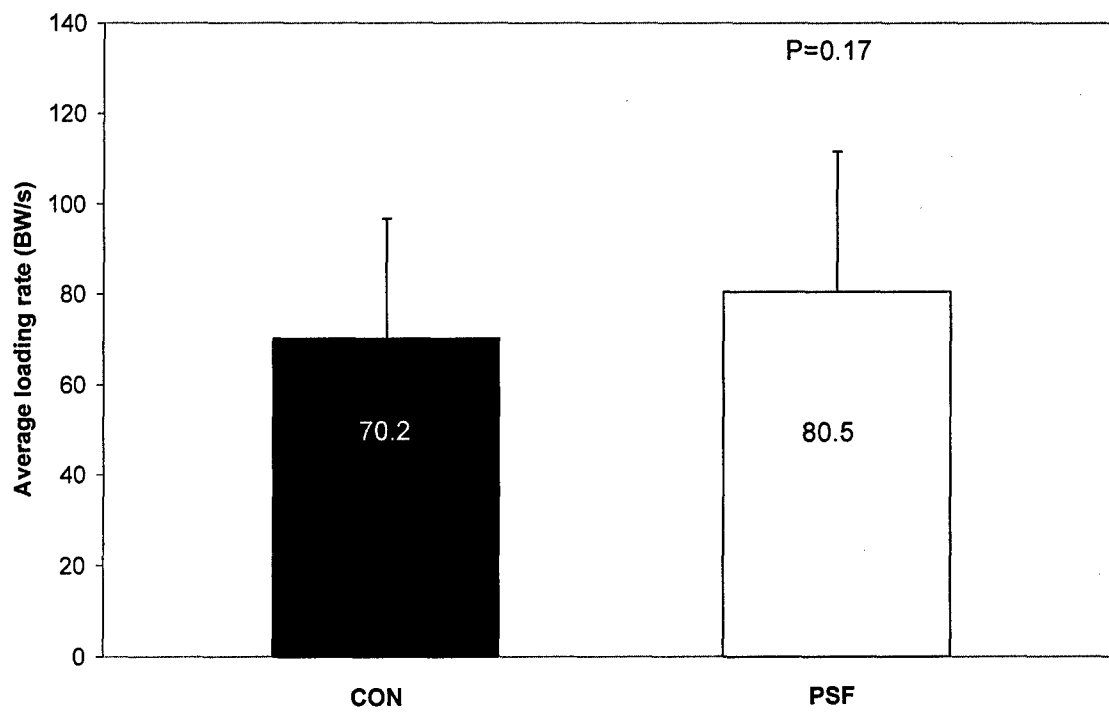


Figure 10: Average loading rate in subjects who developed a stress fracture versus healthy controls.

**Hypothesis 3.2: Runners who sustained a PSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.**

There was a large increase (56%) in peak positive tibial acceleration in the PSF group, compared to the controls (Fig. 11). No statistical differences in kinematic characteristics were found between the PSF group and the healthy controls (Table 6). This is in agreement with the findings of the retrospective TSF group. However, there was a trend towards an increase in the vertical impact peak and a decrease in knee flexion excursion in the PSF group. The combination of greater impacts and lower joint excursions likely increases the loading experienced by the lower extremity.

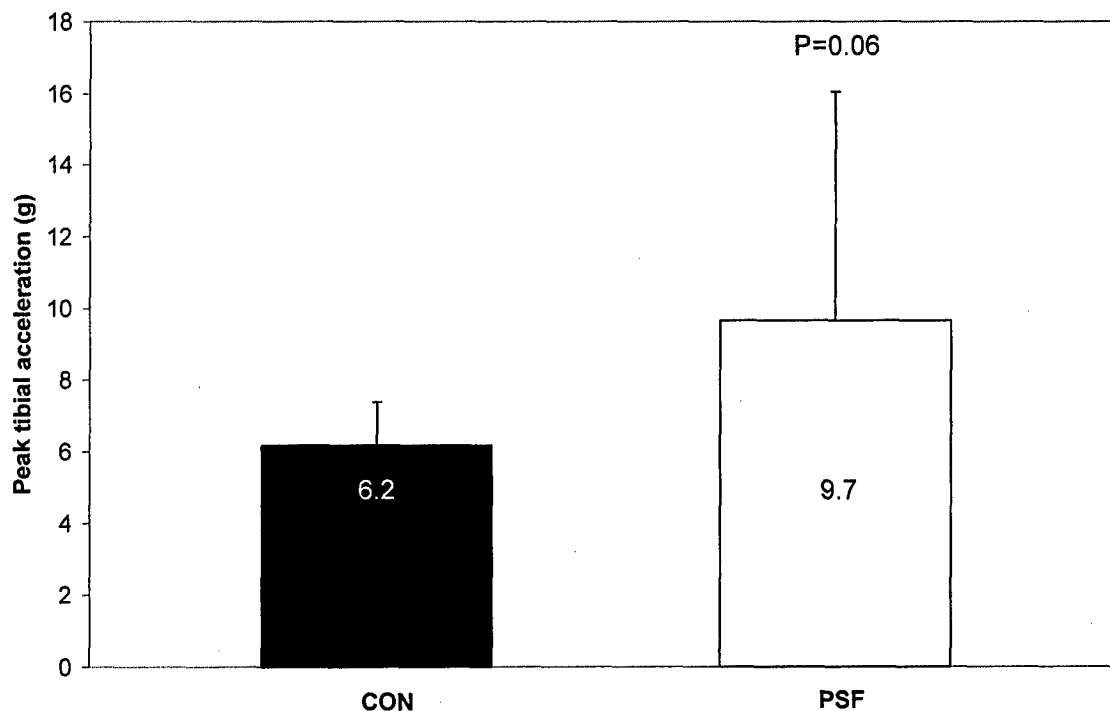


Figure 11: Peak positive tibial acceleration in subjects who developed a stress fracture versus healthy controls.

**Hypothesis 3.3: Runners who sustained a PSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.**

This group of PSF subjects demonstrated a 17% decrease in tibial area moment of inertia compared to the control group (Fig. 12), however this was not statistically significant. They also showed a 29% decrease in tibial varum, which is opposite to what we expected (Fig. 13). This is in contrast to the RTSF group, which showed no differences in structural measures between the injured and control groups.

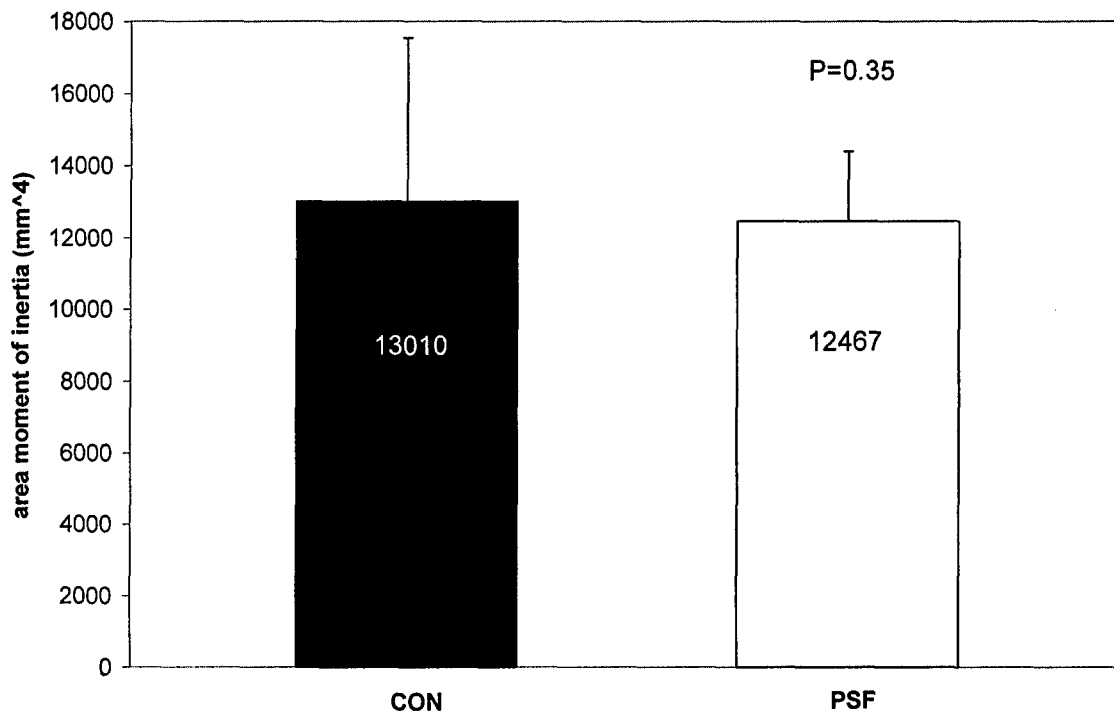


Figure 12: Tibial area moment of inertia in subjects who developed a lower extremity stress fracture versus healthy controls.

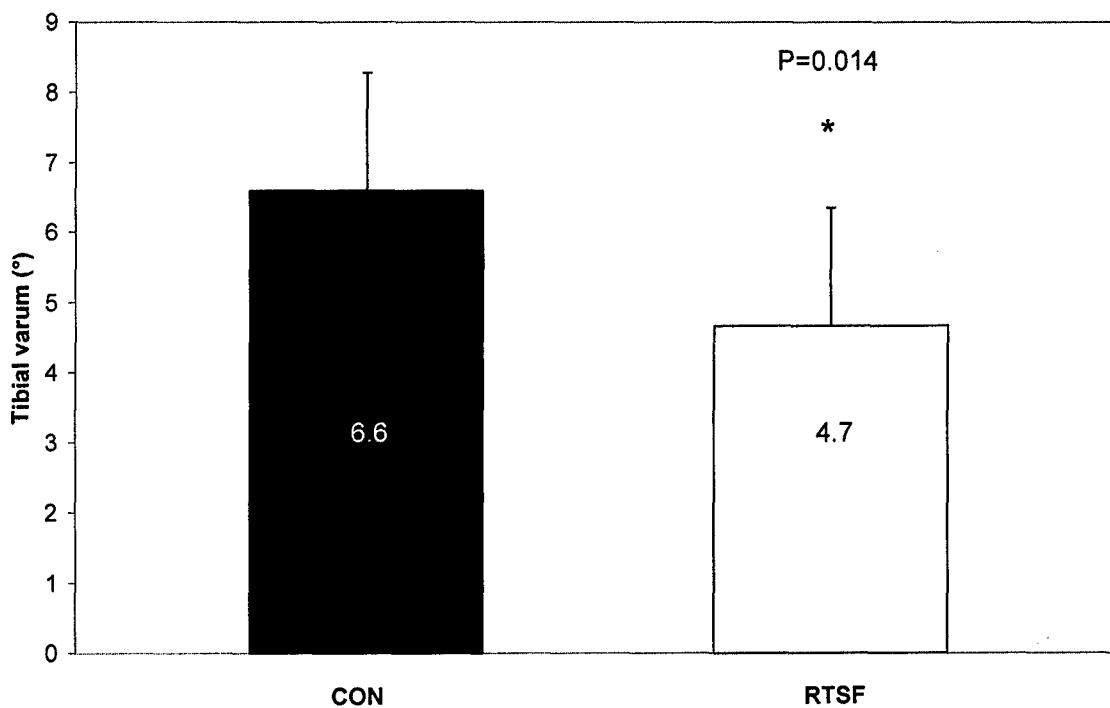


Figure 13: Tibial varum in subjects who developed a lower extremity stress fracture versus healthy controls (\* = significantly less than controls).



Table 6: Variables that showed no difference between subjects who had a previous stress fracture and healthy controls.

	<b>PSF</b>	<b>CON</b>	<b>P value</b>
Impact peak (BW)	1.91 ± 0.39	1.73 ± 0.35	0.10*
Peak vertical force (BW)	2.46 ± 0.20	2.49 ± 0.13	0.27
Peak braking force (BW)	-0.37 ± 0.08	-0.38 ± 0.05	0.35
Braking instantaneous load rate (BW/s)	20.15 ± 6.95	19.98 ± 6.24	0.47
Braking average load rate (BW/s)	7.73 ± 3.15	8.84 ± 3.42	0.18
Vertical leg stiffness (kN/m)	8.32 ± 1.34	8.95 ± 1.41	0.12
Ankle joint stiffness (Nm/mass*ht <sup>o</sup> )	0.36 ± 0.31	0.36 ± 0.46	0.50
Knee joint stiffness (Nm/mass*ht <sup>o</sup> )	0.048 ± 0.011	0.047 ± 0.01	0.40
Ankle dorsiflexion excursion (°)	20.06 ± 3.20	21.79 ± 4.16	0.12
Knee flexion excursion (°)	-30.67 ± 6.24	-33.75 ± 4.97	0.07*

\* indicates a trend in the data, i.e.  $p \leq 0.10$

#### **4) Summary of pre and post injury data from eight prospective lower extremity stress fractures**

Aim 4: Compare mechanics of individuals with healed tibial stress fractures (or tibial stress reactions) to their mechanics prior to the fracture to determine whether compensation for injury occurs.

With the relatively small number of participants who have experienced tibial stress fractures prospectively and returned for a reassessment, we have extended this comparison to include all lower extremity stress fractures. Results for each of those variables that were significantly different between the RTSF group and its control group are presented in tabular form to enable trends in the data to be observed (Tables 7 – 11). In the case of tibial shock, two subjects do not have pre-injury data, due to accelerometer hardware problems encountered during data collection. One missing pre-injury knee stiffness value is due to problems encountered during data processing. Again, we consider group changes of 15% or more to be clinically significant. With the addition of more subjects in the future, statistical analysis will be performed..

**Hypothesis 4.1: Runners with healed TSFs would not exhibit changes in kinetic variables including instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to their pre-injury status.**

Table 7: Vertical instantaneous loading rate for eight prospective lower extremity stress fracture subjects pre and post injury (BW/s)

<b>Subject</b>	<b>PRE</b>	<b>POST</b>	<b>% Difference</b>
1	131.41	162.10	23.4
2	66.87	68.37	2.2
3	94.75	85.77	-9.5
4	72.19	64.93	-10.0
5	64.82	71.00	9.5
6	136.24	167.43	22.9
7	102.88	69.48	-32.5
8	87.98	88.06	0.1
<b>Group Mean</b>	<b>95.59</b>	<b>98.44</b>	<b>0.77</b>

Table 8: Vertical average loading rate for eight prospective lower extremity stress fracture subjects pre and post injury (BW/s).

<b>Subject</b>	<b>PRE</b>	<b>POST</b>	<b>% Difference</b>
1	112.21	140.32	25.1
2	44.16	50.80	15.0
3	86.83	70.42	-18.9
4	67.14	60.41	-10.0
5	59.01	64.72	9.7
6	123.56	150.79	22.0
7	80.35	46.37	-42.3
8	79.82	82.85	3.80
<b>Group Mean</b>	<b>81.90</b>	<b>83.40</b>	<b>0.55</b>

Table 9: Average loading rate during braking for eight prospective lower extremity stress fracture subjects pre and post injury (BW/s).

Subject	PRE	POST	% Difference
1	10.52	10.44	-0.7
2	9.04	7.85	-13.1
3	3.07	6.69	117.7
4	6.40	7.98	24.8
5	3.56	2.74	-23.2
6	9.42	16.46	74.7
7	11.32	19.29	70.4
8	5.34	5.93	11.13
<b>Group Mean</b>	<b>7.62</b>	<b>10.21</b>	<b>32.7</b>

Table 10: Knee joint stiffness for eight prospective lower extremity stress fracture subjects pre and post injury (Nm/mass\*ht<sup>3</sup>).

Subject	PRE	POST	% Difference
1	0.05	0.06	11.2
2	0.06	0.05	-17.9
3	0.03	0.05	93.9
4	0.04	0.04	-9.0
5	0.04	0.06	38.5
6	0.04	0.05	50.0
7	0.04	0.06	50.5
8	-	(0.05)	-
<b>Group Mean</b>	<b>0.04</b>	<b>0.05</b>	<b>31.0</b>

**Hypothesis 4.2: Runners with healed TSFs would not exhibit changes in kinematic variables including peak tibial acceleration, ankle dorsiflexion excursion and knee flexion excursion compared to their pre-injury status.**

Table 11: Peak positive tibial acceleration for eight prospective lower extremity stress fracture subjects pre and post injury (g).

Subject	PRE	POST	% Difference
1	16.15	14.28	-11.5
2	9.13	8.23	-9.9
3	-	(6.99)	-
4	4.07	5.29	29.8
5	-	(5.30)	-
6	9.85	17.59	78.5
7	10.18	12.76	25.3
8	6.36	6.63	4.1
<b>Group Mean</b>	<b>9.88</b>	<b>11.63</b>	<b>19.4</b>

While the responses are variable, there is a general trend of increased anteroposterior loading rates during braking, but not vertical loading characteristics. These shear loading rates indicate the magnitude of bending loads that the lower extremity is subject to, in addition to the compressive loading that occurs during initial weight acceptance in stance. It has been shown that anterior-posterior bending strength is related to the risk of tibial stress fracture (Milgrom et al., 1989). Therefore, the magnitude of anterior-posterior loading rates may be directly related to stress fracture. The secondary planes of ground reaction force are often overlooked in gait analyses, but these substantial changes indicate that they are worthy of further investigation in relation to stress fracture injuries in runners.

An increase in knee joint stiffness is also apparent. Furthermore, an increase in tibial shock occurred following recovery from injury. Since stress fractures are essentially fatigue fractures of the bone, their occurrence relates to the load per cycle and the number of cycles. Increasing either of these factors increases the risk of exceeding the fatigue limit of the tissue. Both loading rates during braking and tibial shock indicate the magnitude of compression loading per cycle, therefore higher values indicate increased risk.

These data suggest that runners who sustain a stress fracture are adopting an even more risky gait following recovery from stress fracture. This finding may help to explain the high incidence of reinjury following a lower extremity stress fracture in runners.

Since only a small number of subjects have so far returned for a post-injury visit following lower extremity stress fracture, these data provide only a suggestion of the changes that may occur following recovery from such an injury. As more tibial stress fractures occur in the study population, and return visits are made following recovery and return to full training, statistical analysis of the changes will be carried out to determine whether there is a change between pre and post tibial stress fracture mechanics.

If these findings are seen consistently as additional subjects are added, there may be a need to retrain their gait patterns to reduce the risk of recurring stress fractures. In addition, if differences between pre and post injury mechanics persist, this provides further support that prospective studies may be needed.

## **5) List of Publications**

Since the last report, six additional abstracts have been submitted and were accepted for presentation. Three abstracts were presented at the American College of Sports Medicine National Meeting in Indianapolis, Indiana and three will be presented at the American Society of Biomechanics Annual Meeting in Portland, Oregon in September 2004. These abstracts are included in Appendix A and the references are provided below.

Davis, I., Milner, C. & Hamill, J. (2004). Does increased loading during running lead to tibial stress fractures? A prospective study. *Medicine and Science in Sports and Exercise*, 36, S58.

Davis, I.S., Milner, C.E. & Hamill, J. (2004). Prospective Study of Structural and Biomechanical Factors associated with the Development of Plantar Fasciitis in Female Runners. *Book of Abstracts 2004 American Society of Biomechanics Annual Meeting*, Portland, Oregon.

Dierks, T.A. & Davis, I. (2004). Lower extremity joint coupling and patellofemoral joint pain during running. *Medicine and Science in Sports and Exercise*, 36, S56.

Dierks, T.A., Davis, I.S. & Hamill, J. (2004). Lower extremity joint coupling in runners who developed patellofemoral pain syndrome. *Book of Abstracts 2004 American Society of Biomechanics Annual Meeting*, Portland, Oregon.

Milner, C., Davis, I. & Hamill, J. (2004). Is free moment related to tibial stress fracture in distance runners? *Medicine and Science in Sports and Exercise*, 36, S57.

Milner, C.E., Davis, I.S. & Hamill, J. (2004). Does sustaining a lower extremity stress fracture alter lower extremity mechanics in runners? *Book of Abstracts 2004 American Society of Biomechanics Annual Meeting*, Portland, Oregon.

From the data collected during the first three years, three abstracts were submitted and presented at the American College of Sports Medicine National Meeting in San Francisco, California, the XIXth International Society of Biomechanics Congress in Dunedin, New Zealand and the American Society of Biomechanics Annual Meeting in Toledo, Ohio. The references are provided below.

Ferber, R., McClay Davis, I., Hamill, J. & Pollard, C.D. (2003). Prospective biomechanical investigation of iliotibial band syndrome in competitive female runners. *Medicine and Science in Sports and Exercise*, 35, S91.

McClay Davis, I., Ferber, R., Hamill, J. & Pollard, C.D. (2003). Rearfoot mechanics in competitive runners who had experienced plantar fasciitis. *Book of Abstracts 2003 XIXth International Society of Biomechanics Congress*, Dunedin, New Zealand.

McClay Davis, I., Dierks, T.A. Ferber, R. & Hamill, J. (2003). Lower extremity mechanics in patients with patellofemoral joint pain: a prospective study. *Book of Abstracts 2003 American Society of Biomechanics Annual Meeting*, Toledo, Ohio.

From the data collected during years 1 and 2, three abstracts were submitted and presented at the American College of Sports Medicine National Meeting in St Louis, Missouri and at the World Congress of Biomechanics in Calgary Alberta, Canada. The references are provided below.

McClay Davis, I., Ferber, R., Dierks, T.A., Butler, R.J., & Hamill, J. (2002). Variables associated with the incidence of lower extremity stress fractures. *Book of Abstracts 2002 World Congress of Biomechanics*, Calgary, Alberta, Canada.

Ferber, R., McClay Davis, I., Hamill, J., Pollard, C.D., & McKeown, K.A. (2002). Kinetic variables in subjects with previous lower extremity stress fractures. *Medicine and Science in Sports and Exercise*, **34**, s25.

Pollard, C.D., & McKeown, K.A. Hamill, J., Ferber, R., McClay Davis, I. (2002). Selected structural characteristics of female runners with and without lower extremity stress fractures. *Medicine and Science in Sports and Exercise*, **34**, s991.

From the data collected during year 1, one abstract was submitted and presented at the American Physical Therapists' Association Combined Sections Meeting in Boston, Massachusetts. The reference is provided below.

Multiple Lower Extremity Stress Fractures In A Division I Cross Country Runner: A Case Study. Pollard C.D., McClay I.S., Hamill J. 2001 APTA Combined Sections Meeting, Boston, Massachusetts.

## **6) Presentations made**

In addition to the conference presentations associated with the abstracts detailed in section 3 above, the following presentations were made at the Center for Biomedical Engineering Research Symposium at the University of Delaware, Newark, Delaware on May 14th 2004.

*Lower extremity joint coupling and patellofemoral joint pain during running.*

Dierks, T.A. & Davis, I.

*Does sustaining a lower extremity stress fracture alter lower extremity mechanics in runners?*

Milner, C.E., Davis, I.S. & Hamill, J.

In addition to the conference presentations associated with the abstracts detailed in section 3 above, the following presentation was made in 2003.

*Gait Retraining in Runners: An Application of the VICON Real-Time System*

Presentation made to the Vicon Users' Group Meeting at the Gait and Clinical Movement Analysis Annual Meeting 2003, Wilmington, Delaware, Thursday May 8th, 2003.

## **7) Summary of information from the database**

A summary of all the retrospective and prospective injury information we have collected is presented in tables 6 and 7. It is interesting to note the lower leg remains the most common site of retrospective injuries. Typically, the knee is the most common site of running injuries, with patellofemoral pain being the most common single injury at the knee. In this study, the lower leg is the most common site of injury and tibial stress fractures and syndromes are the most common injury type at this site. We feel this is because we initially advertised this study as a stress fracture study and not as a running injury study. We have since changed this advertising strategy, and find that the difference is not as marked as in previous years.

In the prospective data, the injury pattern is more typical, with the knee being the most common site of injury and patellofemoral pain the second most common knee injury. Furthermore, the incidence of tibial stress fractures and tibial stress reaction is much reduced in the prospective database.

Table 7: Summary of retrospective injury information collected from the website database.

Injury Category		Incidence of Injury
<b>Back</b>	<b>TOTAL</b>	<b>49</b>
	Back sprain	5
	Back strain	25
	Disc pathology	3
	Back other	16
<b>Hip/ groin</b>	<b>TOTAL</b>	<b>56</b>
	Gluteal strain/ tendinitis	1
	Greater trochanteritis	12
	Groin strain/ tendinitis	6
	Pelvic stress fracture	5
	Hip/ groin injury other	32
<b>Thigh</b>	<b>TOTAL</b>	<b>52</b>
	Femoral stress fracture	10
	Hamstring strain	22
	Quadriceps strain	10
	Thigh other	10
<b>Knee</b>	<b>TOTAL</b>	<b>147</b>
	IT band friction syndrome	57
	Lateral collateral strain	1
	Medial collateral strain	1



Medial plica syndrome	1
Patellar tendinitis	13
Patellofemoral pain syndrome	39
Osteoarthritis	1
Pes Anserinus tendinitis	1
Knee other	33
<b>Lower leg</b>	<b>TOTAL</b>
	<b>197</b>
Achilles tendonitis	21
Acute fibular fracture	4
Acute tibial fracture	2
Anterior compartment syndrome	7
Anterior tibialis strain	5
Fibular stress fracture	9
Gastroc/ soleus strain	6
Peroneal strain	2
Tibial stress fracture	41
Tibial stress syndrome	66
Tibialis posterior strain	6
Posterior compartment syndrome	2
Lower leg other	26
<b>Ankle</b>	<b>TOTAL</b>
	<b>82</b>
Lateral ankle sprain	72
Medial ankle sprain	3
Ankle other	7
<b>Foot</b>	<b>TOTAL</b>
	<b>124</b>
Acute metatarsal fracture	4
Metatarsal stress fracture	24
Metatarsal stress syndrome	2
Neuroma	6
Painful 1 <sup>st</sup> MTP joint	3
Plantar fasciitis	45
Retrocalcaneal bursitis	1
Sesamoid fracture	2
Sesamoiditis	4
Tarsal tunnel syndrome	1
Foot other	32
Other, region unspecified	21
<b>TOTAL</b>	<b>728</b>

Table 8: Summary of prospective injury information collected from the website database.

Injury Category		Incidence of Injury
<b>Back</b>	<b>TOTAL</b>	<b>42</b>
	Back sprain	23
	Disc pathology	3
	Back strain	7
	Back other	9
<b>Hip/ groin</b>	<b>TOTAL</b>	<b>92</b>
	Gluteal strain/ tendinitis	8
	Greater trochanteritis	7
	Groin strain/ tendinitis	12
	Hip/ groin injury other	55
	Pelvic stress fracture	10
<b>Thigh</b>	<b>TOTAL</b>	<b>102</b>
	Femoral stress fracture	14
	Hamstring strain	58
	Quadriceps strain	14
	Thigh other	16
<b>Knee</b>	<b>TOTAL</b>	<b>173</b>
	IT band friction syndrome	65
	Medial plica syndrome	1
	Osgood-Schlatter's syndrome	1
	Lateral collateral strain	2
	Patellar tendonitis	12
	Patellofemoral pain syndrome	43
	Pes Anserinus tendinitis	9
	Knee other	40
<b>Lower leg</b>	<b>TOTAL</b>	<b>136</b>
	Achilles tendinitis	20
	Anterior compartment syndrome	14
	Anterior tibialis strain	5
	Fibular stress fracture	1
	Gastroc/ soleus strain	26
	Peroneal strain	5
	Tibial stress fracture	13
	Tibial stress syndrome	21
	Tibialis posterior strain	5
	Acute fibular fracture	1
	Lower leg other	25

<b>Ankle</b>	<b>TOTAL</b>	<b>59</b>
Lateral ankle sprain		42
Medial ankle sprain		5
Ankle other		12
<b>Foot</b>	<b>TOTAL</b>	<b>96</b>
Metatarsal stress syndrome		5
Metatarsal stress fracture		11
Painful 1 <sup>st</sup> MTP joint		3
Acute metatarsal fracture		5
Sesamoiditis		
Neuroma		1
Plantar fasciitis		34
Retrocalcaneal bursitis		3
Sesamoid fracture		1
Foot other		33
Other, region unspecified		47
<b>TOTAL</b>		<b>747</b>

#### **8) Degrees obtained that are supported by this award**

Andrea Fidler was funded on this award and will graduate from the University of Massachusetts with a Master of Science from the Department of Exercise Science in September 2003.

Christine Pollard was funded on this award and will graduate from the University of Massachusetts with a Ph.D. from the Department of Exercise Science in September 2003. Reed Ferber was funded for a two-year Post-doctoral Research Fellowship and graduated from the University of Delaware in July 2003.

Kelly Anne McKeown was funded on this award and graduated from the University of Massachusetts with a Master of Science from the Department of Exercise Science in April of 2002.

#### **9) Employment or research opportunities applied for and/ or received based on experience/ training supported by the grant**

Reed Ferber has secured a post-doctoral research fellowship in the Human Performance Laboratory at the University of Calgary, Alberta, Canada. Christine Pollard is currently working as a post-doctoral research fellow at the University of Southern California. Kelly Anne McKeown is currently working as the biomechanist in the Shriners' Hospital Motion Analysis Laboratory in Springfield, MA.

## CONCLUSIONS.

This Annual Report focused on the fourth year status of this investigation. Six specific work objectives were outlined and discussed with respect to adherence and methods used to meet all objectives in a timely manner. While there a slight lag in the number of subjects recruited, measures that were taken in 2002 and 2003 to increase recruitment efforts were successful and continue to be employed. We have now recruited 396 subjects and will continue to recruit subjects in the high risk subgroup of young, high mileage runners. We hope this will provide us with more prospective tibial stress fractures in the coming 12 months.

To date, data on 396 subjects have been collected and analyses performed on retrospective tibial stress fractures, prospective tibial stress fractures and reactions, and four subjects who had experienced a tibial stress fracture or reaction during the study and returned for reassessment of their running mechanics following recovery and a return to training. In addition, six new conference abstracts were presented on tibial stress fractures, plantar fasciitis and patellofemoral pain, highlighting the wide spectrum of injuries that this database is providing valuable information about. Two manuscripts are in final preparation for publication, one relating lower extremity mechanics to the incidence of tibial stress fracture and the other is a prospective study of iliotibial band injuries. A third manuscript relating to the free moment of vertical ground reaction force and tibial stress fractures will be submitted by the end of the year.

Overall, based on these preliminary data, it appears that certain loading parameters such as loading rates, peak shock, and knee joint stiffness are related to the development of stress fractures. Once we further validate these findings with additional data, we will be able to develop a simple screening tool to predict those at increased risk for stress fractures. In addition, we are in the process of developing protocols of realtime biofeedback in order to reduce loading during gait and thus reduce the risk of these stress-related injuries.

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## **Appendix 1**

### **Abstracts Presented at National and International Conferences.**

**1) DOES INCREASED LOADING DURING RUNNING LEAD TO TIBIAL STRESS FRACTURES? A PROSPECTIVE STUDY**

Presented at the American College of Sports Medicine National Meeting,  
Indianapolis, Indiana.

**2) PROSPECTIVE STUDY OF STRUCTURAL AND BIOMECHANICAL FACTORS ASSOCIATED WITH THE DEVELOPMENT OF PLANTAR FASCIITIS IN FEMALE RUNNERS**

Presented at the American Society of Biomechanics Annual Meeting,  
Portland, Oregon.

**3) LOWER EXTREMITY JOINT COUPLING AND PATELLOFEMORAL JOINT PAIN DURING RUNNING**

Presented at the American College of Sports Medicine National Meeting,  
Indianapolis, Indiana.

**4) LOWER EXTREMITY JOINT COUPLING IN RUNNERS WHO DEVELOPED PATELLOFEMORAL PAIN SYNDROME**

Presented at the American Society of Biomechanics Annual Meeting,  
Portland, Oregon.

**5) IS FREE MOMENT RELATED TO TIBIAL STRESS FRACTURE IN DISTANCE RUNNERS?**

Presented at the American College of Sports Medicine National Meeting,  
Indianapolis, Indiana.

**6) DOES SUSTAINING A LOWER EXTREMITY STRESS FRACTURE ALTER LOWER EXTREMITY MECHANICS IN RUNNERS?**

Presented at the American Society of Biomechanics Annual Meeting,  
Portland, Oregon.

## Does increased loading during running lead to tibial stress fractures? A prospective study

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Stress fractures are among the most serious injuries a runner can sustain. The majority of these fractures occur in the tibia, and females are twice as likely to sustain this injury compared to males. Stress fractures are thought to be related, in part, to abnormal loading during running. While retrospective studies are informative, prospective studies are essential to establish cause and effect. **PURPOSE:** The purpose of this study was to examine, prospectively, the relationship between measures of increased loading and the incidence of tibial stress fractures (TSF) in competitive women runners. It was hypothesized that runners who sustained a TSF would have greater tibial shock, peak vertical forces, vertical loading rates and lower extremity stiffness than those who did not experience one. **METHODS:** Currently 5 runners have sustained a documented TSF or tibial stress reaction, the precursor to TSF. Five age and mileage matched runners served as controls. Tibial accelerometry and ground reaction forces were collected at 960 Hz as subjects traversed a force plate centered on a 25 m runway at 3.8 m/s. Five trials were averaged for the analysis. Peak positive acceleration (PPA), peak vertical ground reaction force (PVGRF), instantaneous load rate (ILR) and average load rate (ALR), as well as lower extremity stiffness (K) were all examined.

### RESULTS:

	PPA(g)	PVGRF(bw)	ILR (bw/s)	ALR (bw/s)	K (kN/m)
TSF	9.06	2.55	112.88	88.20	9.21
Controls	<b>4.73</b>	<b>2.63</b>	<b>81.03</b>	<b>62.91</b>	<b>9.63</b>
P	0.06	0.15	0.04	0.06	0.30

While these data are preliminary, they appear to suggest that runners who sustain a tibial stress fracture exhibit evidence of increased lower extremity loading, including increased tibial shock, and instantaneous and average vertical loading rates, prior to injury. While stiffness has been shown to be related to load rate, increases in lower extremity stiffness were not found in these subjects.

**CONCLUSIONS:** Based upon the results of these preliminary data, it appears that tibial shock and vertical load rates are increased in female runners who develop TSF.

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# Prospective Study of Structural and Biomechanical Factors associated with the Development of Plantar Fasciitis in Female Runners

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## INTRODUCTION

Plantar fasciitis is one of the 5 most common injuries that runners sustain (vanMechelen, 1992). It is believed that this injury is a result of repetitive strain to the plantar fascia. Warren et al. (1987) reported that runners, either currently or formerly experiencing PF, exhibited greater pronation of the foot while in a loaded stance position than runners with no history of this injury.

In a retrospective study of runners with a history of plantar fasciitis, we reported that these runners exhibited significantly greater peak eversion compared to the controls (Davis et al, 2003). A trend towards greater eversion velocity was also noted. Plantar fasciitis is also often associated with limitations in ankle dorsiflexion range of motion. It is believed that this limitation may lead to a compensatory excessive pronation. This excessive pronation, noted at both the rearfoot and midfoot, leads to increased strain of the plantar fascia.

Finally, it is possible that excessive loading, in terms of peak forces and rates of loading, may be associated with the development of plantar fasciitis. However, these loading variables have yet to be examined in runners who develop this injury.

Therefore, the purpose of this prospective study was to compare foot structure and mechanics in a group of female runners who develop plantar fasciitis (PF) to a group of healthy controls (CON). It was hypothesized the PF group would exhibit decreased peak

ankle dorsiflexion, increased rearfoot eversion, and increased vertical ground reaction forces and load rates. Structurally, it was expected that the PF group would have lower arches, greater calcaneal eversion in stance and limited ankle dorsiflexion range.

## METHODS

These data are part of an ongoing, prospective study of female distance runners. Female runners, aged 18 to 40 yrs., and running at least 20 miles per week are recruited into a 2-year longitudinal study. A gait analysis is performed on entry into the study. Subjects run overground at 3.7m/s in standard laboratory running shoes. Five trials are recorded using a 6-camera motion capture system at 120 Hz (Vicon, Oxford Metrics, UK) and a force platform (Bertec, OH, USA). 3D kinematics and kinetics were calculated for both lower extremities (Visual 3D, C-Motion, MD, USA). In addition to the motion analysis, a structural assessment of the runner's lower extremities is performed by an experienced physical therapist. Included in these measures are arch index (Williams et al, 2000), dorsiflexion range of motion with the knee extended, and calcaneal valgus during stance.

The subjects are then followed monthly for two years. Running mileage and injuries are tracked. To date, 10 runners, aged  $32 \pm 8$  years, and running an average of  $28 \pm 12$  miles per week have developed plantar fasciitis (PF). These were compared to a

control (CON) group of 10 uninjured runners matched for age ( $31 \pm 11$  yrs) and mileage ( $28 \pm 6$  miles per week).

Variables of interest were compared between groups statistically using an independent, one-tailed t-test. Due to the preliminary nature of these data, a p value of 0.10 was used for statistical significance.

## RESULTS AND DISCUSSION

Comparison of the variables of interest between groups is presented in Table 1.

**Table 1:** Structural and Dynamic Measures

	PF	CON	p
Peak EV (deg)	7.1	8.6	0.22
DF exc (deg)	17.8	20.8	0.12
Peak DF (deg)	25.7	27.7	0.15
Imp. Peak (BW)	1.81	1.65	0.15
Inst. Load Rate (BW/s)	124.5	109.3	0.19
Avg. Load Rate (BW/s)	86.7	77.9	0.22
Stance Calc. VAL (deg)	5	2	0.03
Arch Index (unitless)	0.339	0.353	0.19
DF rom (deg)	1	3	0.18

Surprisingly, no difference was noted in peak rearfoot eversion (EV). This is in contrast to our previous retrospective study of plantar fasciitis (Davis et al, 2003), where the injured subjects exhibited significantly greater EV than the controls. While not statistically significant, there was a trend towards a decrease in peak dorsiflexion (DF) and DF excursion. This was not associated with increased rearfoot EV in this group. However, the reduction in DF may have resulted in a compensation in the midfoot (not readily measured with standard motion analysis techniques). It is this midfoot pronation that is believed to most directly increase the strain of the plantar fascia.

All loading variables were higher in the PF group, with impact peak showing the strongest trend. Instantaneous vertical load rate was 15% higher in the PF group. Higher load rates may mean greater strain rates on soft tissues, such as the plantar fascia. These loading variables have not

been previously examined in this group and may be important in the development of plantar fasciitis.

Structurally, the PF group had slightly lower arches. In addition, they presented with less ankle dorsiflexion range of motion. This may have resulted in the decreased peak dorsiflexion and dorsiflexion excursion seen during running. Finally, the PF group exhibited significantly greater calcaneal EV in stance, consistent with Warren et al. (1987). It was expected that this would be associated with greater rearfoot EV during running. While the structural measure was taken from markers placed directly on the skin, the dynamic measures were from markers placed on the shoe. This factor may have added unexplained variance to the dynamic rearfoot EV angle.

## SUMMARY

Results of these preliminary, prospective data suggest that there may be predisposing structural and mechanical factors to the development of plantar fasciitis. These results may be strengthened as additional subjects are added. With additional subjects, regression analyses, utilizing both structural and mechanical variables will be performed. It is hoped that, as this research progresses, we will gain further insight into the cause of plantar fasciitis in runners. This will help us to develop optimal treatment interventions for this common injury.

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## Lower Extremity Joint Coupling and Patellofemoral Joint Pain During Running

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Patellofemoral joint pain (PFP) is the most prevalent pathology in runners. Abnormalities in joint coupling, in terms of timing differences, phasing relationships, and continuous excursion ratios, have been suggested to be sources of running related injuries. However, few studies have examined these parameters in an injured population. **PURPOSE:** To compare joint coupling in runners who have a history of PFP and those who have not by methods of timing differences, continuous relative phase (CRP), and coupling angles (CA). **METHODS:** As part of an ongoing study, 13 females with a history of PFP were compared to 13 uninjured females. All were competitive runners (minimum 20 miles/week) and uninjured at the time of data collection. Five trials of ground reaction force (GRF) data and kinematic data were collected during overground running at a speed of  $3.65 \pm 0.2$  m/s. The stance phase was divided into four periods based on events of the GRF. Various joint coupling relationships of rearfoot eversion/inversion, tibial internal/external rotation, knee flexion/extension, and knee internal/external rotation were assessed. Timing difference values of 0% stance indicated synchronous coupling. CRP values of 0° indicated in-phase relationships between the two motions of interest while coupling angles of 45° inferred relatively equal excursions between the two motions. **RESULTS:**

		RF(ev/in)-K(f/e)		RF(ev/in)-T(rot)		T(rot)-K(f/e)		RF(ev/in)-K(rot)		T(rot)-K(rot)	
		PFP	Con	PFP	Con	PFP	Con	PFP	Con	PFP	Con
<b>Timing<sup>^</sup></b>		3.5	2.8	**10.4	3.9	**6.9	-1.1	**3.6	-9.0	-14.0	-12.9
<b>CRP<sup>^^</sup></b>	<b>P1</b>	*-7.63	-24.12	33.43	21.66	-41.05	-45.79	1.40	-12.41	-32.03	-34.07
	<b>P2</b>	**13.74	-21.35	-0.68	5.37	*-13.06	-26.72	-30.20	-29.82	-29.53	-35.19
	<b>P3</b>	-7.87	-5.70	**21.15	-6.29	**13.28	-0.23	-7.30	-0.86	13.85	5.43
	<b>P4</b>	-6.60	6.56	3.96	12.46	**10.56	-19.02	25.17	25.67	21.21	13.21
<b>CA<sup>^^</sup></b>	<b>P1</b>	29.11	31.20	60.54	56.37	*17.47	23.44	**51.11	58.52	*36.94	48.69
	<b>P2</b>	*24.22	20.35	60.84	62.01	*15.65	11.79	49.79	51.40	34.43	34.73
	<b>P3</b>	**24.55	22.20	55.52	55.74	18.13	16.73	50.40	52.49	39.71	42.53
	<b>P4</b>	32.09	30.60	60.77	56.39	19.28	22.06	55.93	58.03	40.06	44.81

<sup>^</sup>Timing Differences only between motions in first half of stance.

<sup>^^</sup>P1 - P4 are the 4 periods of stance.

\*Independent t-test of  $p < 0.10$ . \*\* $p < 0.15$ .

**CONCLUSION:** These preliminary data suggest that runners with a history of PFP may exhibit differences in joint timing, phasing relationships, and continuous excursion ratios. Differences were primarily observed between the tibial internal/external rotation with knee flexion/extension relationship, followed by the rearfoot eversion/inversion with knee flexion/extension relationship.

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# **LOWER EXTREMITY JOINT COUPLING IN RUNNERS WHO DEVELOPED PATELLOFEMORAL PAIN SYNDROME**

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## **INTRODUCTION**

Patellofemoral Pain Syndrome (PFPS) is one of the most prevalent running overuse injuries, yet the mechanisms of PFPS are still not well understood. Most PFPS studies have examined joint motions in isolation. However, it has been suggested that abnormalities in joint coupling between the foot, shank, and thigh may be related to running injuries (Bates et al. 1978). To evaluate joint coupling, various methods have been used (Table 1). Timing differences assess coupling at distinct points during stance. The continuous relative phase (CRP) and vector coding methods examine coupling throughout all of stance. Few studies have used these methods in an injured population. To date, there are no prospective studies comparing joint coupling in runners who develop PFPS and uninjured runners, which may lend insight into causative mechanisms. Therefore, the purpose of this study was to compare, prospectively, joint coupling in female runners who later develop PFPS to uninjured runners who did not develop PFPS. It was hypothesized that PFPS coupling would be less synchronous and more out-of-phase.

## **METHODS**

All data are part of an ongoing prospective running injury study of female competitive distance runners. To date, 15 have developed PFPS. Data were collected prior to developing PFPS and were compared to 15 mileage matched runners from the same study who have not developed an injury to

date. Subjects ran along a 25m runway at a speed of 3.65m/s ( $\pm 5\%$ ). Ground reaction force (GRF) data (960 Hz) and kinematic data (120 Hz, filtered at 8 Hz) were collected. For each subject, coupling variables from the 4 methods (Table 1) were computed for 8 individual trials and averaged. Group means and standard deviations were then calculated. The CRP was derived from the angles and velocities of two joint motions, with a CRP value of 0° meaning the two joint motions were in-phase (Hamill et al. 1999). Vector coding was derived from angle-angle plots, with coupling angles of 45° relating to equal movement between the two joint motions (Heiderscheit et al. 2002). Both CRP and vector coding were assessed during 4 periods of stance, which were based on events of the vertical GRF. One-tailed independent t-tests were used with  $p \leq 0.10$ , due to the preliminary nature of the data.

## **RESULTS AND DISCUSSION**

Table 1: Definition of terms and joint coupling relationships.

<b>Movement Terms (plane and reference)</b>	
EV	Rearfoot eversion. (Frontal, Calcaneus to Tibia.)
TIR	Tibial internal rotation. (Transverse, Calcaneus to Tibia.)
KF	Knee flexion. (Sagittal, Tibia to Femur.)
KIR	Knee internal rotation. (Transverse, Tibia to Femur.)
KADD	Knee adduction. (Frontal, Tibia to femur.)
<b>Timing Differences (measure of synchrony)</b>	
EV-TIR	Time to peak EV minus time to peak TIR.
EV-KF	Time to peak EV minus time to peak KF.
EV-KIR	Time to peak EV minus time to peak KIR.
EV-KADD	Time to peak EV minus time to peak KADD.
TIR-KF	Time to peak TIR minus time to peak KF.
TIR-KIR	Time to peak TIR minus time to peak KIR.
<b>CRP (phasing relationship) &amp; Vector Coding (continuous excursion ratio)</b>	
$RF_{(ev/in)}-K_{(te)}$	Rearfoot EV & inversion coupled with KF & knee extension.
$RF_{(ev/in)}-K_{(rot)}$	Rearfoot EV & inversion coupled with KIR & knee external rotation.
$RF_{(ev/in)}-T_{(rot)}$	Rearfoot EV & inversion coupled with TIR & tibial external rotation.
$RF_{(ev/in)}-K_{(ad/ab)}$	Rearfoot EV & inversion coupled with KADD & knee adduction.
$T_{(rot)}-K_{(te)}$	TIR & tibial external rotation coupled with KF & knee extension.
$T_{(rot)}-K_{(rot)}$	TIR & tibial external rotation coupled with KIR & knee external rotation.

In general, PFPS runners displayed greater time between peaks, suggesting less synchrony (Table 2). PFPS runners were significantly less synchronous for TIR-KF, due to TIR reaching its peak before KF. PFPS runners were significantly more synchronous for EV-KADD, due to uninjured runners reaching peak KADD sooner. The delay in the KADD reversal and the earlier reversal in TIR may result in a malalignment of the patella, which may predispose a runner to PFPS. In general, CRP results suggested that PFPS runners were more out-of-phase. CRP relationships involving tibial rotation resulted in PFPS runners displaying significantly more out-of-phase coupling during period 3 (Figure 1). Period 3 typically follows, and may include, maximum loading and joint reversals. This out-of-phase coupling may be a result of an earlier TIR reversal (noted in timing differences), which may affect load distributions. For  $RF_{(ev/in)}-K_{(ad/ab)}$ , periods 1 and 3 were more in-phase for PFPS runners while period 2 was more out-of-phase (Figure 1). This is most likely a result of the later KADD reversal in PFPS runners. For  $RF_{(ev/in)}-K_{(f/e)}$ , PFPS runners were significantly more out-of-phase during

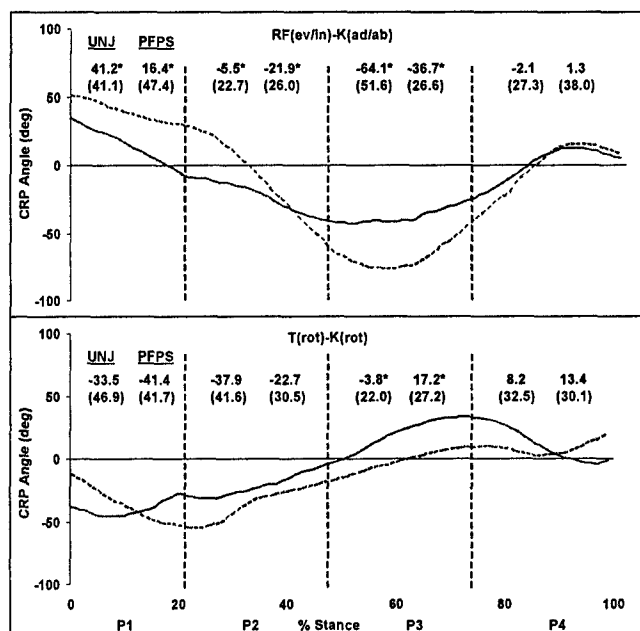


Figure 1: Selected ensemble CRP curves & standard deviations ( ). P1 through P4 indicates the 4 periods of stance. UNJ=uninjured. Dashed curve=UNJ, Solid curve=PFPS. \* $p \leq 0.10$ .

Table 2: Timing differences & standard deviations ( ). A negative value indicates that the proximal motion reached its peak first. \* $p \leq 0.10$ . Values are % of stance.

	EV-TIR	EV-KF	EV-KIR
Uninjured	5.0 (8.0)	5.5 (5.1)	-6.5 (9.5)
PFPS	8.6 (10.8)	3.7 (4.7)	-7.7 (10.8)
	EV-KADD*	TIR-KF*	TIR-KIR
Uninjured	14.2 (14.0)	0.5 (7.8)	-11.5 (11.1)
PFPS	5.2 (17.4)	-4.9 (11.3)	-16.1 (14.0)

periods 1 and 2. Overall, vector coding results were similar. However, the relationships involving tibial rotation suggested that PFPS runners displayed less relative tibial external rotation during period 4 (Figure 2). In contrast, PFPS runners displayed greater relative tibial rotation during period 3 for  $T_{(rot)}-K_{(f/e)}$ .

## SUMMARY

The preliminary results of this study suggest that, prior to the development of PFPS, female runners display differences in joint coupling when compared to those that do not develop PFPS. These differences appear to occur in coupling relationships involving tibial rotation or knee adduction/abduction.

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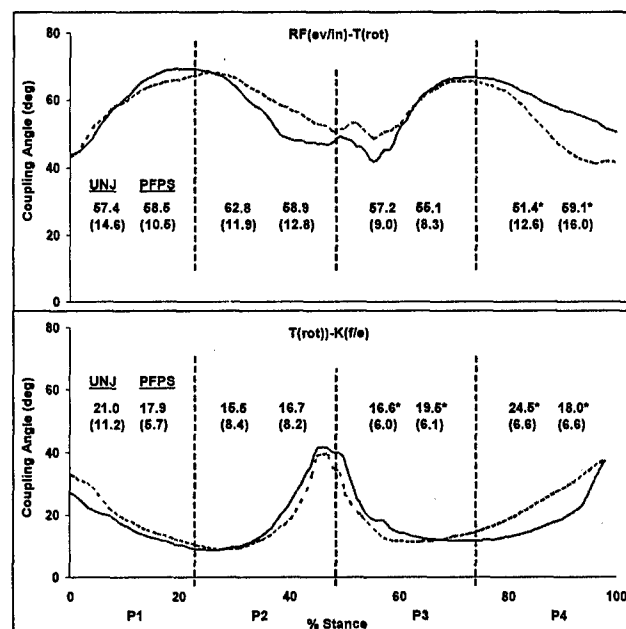


Figure 2: Selected ensemble vector coding curves & standard deviations ( ). P1 through P4 indicates the 4 periods of stance. UNJ=uninjured. Dashed curve=UNJ, Solid curve=PFPS. \* $p \leq 0.10$ .

### Is free moment related to tibial stress fracture in distance runners?

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Stress fractures are common in distance runners with the tibia being particularly susceptible. A stress fracture is arguably the most serious running overuse injury and occurs twice as frequently in female runners than in males. Free moment (FM) is the torsional force about a vertical axis due to friction between the foot and the ground during stance. Its possible role in lower extremity injury has not been widely studied. **PURPOSE:** The purpose of this study was to investigate the relationship between free moment variables and the occurrence of tibial stress fractures (TSF) in female distance runners. It was hypothesized that runners who had previously sustained a TSF would exhibit higher maximum free moment earlier in stance, spend more of stance with FM positive and have higher net angular impulse than runners who had not. **METHODS:** Healthy runners who had sustained TSF previously (n = 13) and an age and mileage matched control group (n = 13) ran at 3.8m/s on a 25m runway containing a force platform sampling at 960 Hz. Data from five trials were normalized to body weight and height and averaged for statistical analysis. Maximum free moment (MAXFM), time to MAXFM (TTMAXFM), per cent stance with FM positive (%POSFM), net angular impulse (IMP), FM at peak vertical ground reaction force (FMVGRF) and FM at peak braking force (FMBRAK) were examined. **RESULTS:** (MAXFM, FMVGRF, FMBRAK values are  $\times 10^{-3}$ , IMP is  $\times 10^{-4}$ )

	MAXFM	TTMAXFM	%POSFM (%)	IMP (s)	FMVGRF	FMBRAK
		(%)				
TSF	8.29	26.80	53.05	1.19	2.61	1.25
Controls	9.49	35.82	54.80	3.49	5.54	4.39
p	0.24	0.02	0.39	0.15	0.06	0.07

These data indicate that runners with a history of tibial stress fracture reach MAXFM earlier in stance. The magnitudes of MAXFM and %POSFM and IMP were the same in both groups. FMVGRF and FMBRAK showed a trend towards lower values in the TSF group; this may be related to the difference in timing of MAXFM. **CONCLUSIONS:** MAXFM occurs earlier in stance in runners who have sustained a TSF previously compared to a control group. Prospective investigations into TSF and FM are needed to determine cause and effect in this relationship and whether TTMAXFM is a marker of TSF risk.

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# DOES SUSTAINING A LOWER EXTREMITY STRESS FRACTURE ALTER LOWER EXTREMITY MECHANICS IN RUNNERS?

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## INTRODUCTION

Stress fractures are common in runners, particularly in females who sustain approximately twice as many as males. A stress fracture is one of the most serious running injuries, requiring six to eight weeks rest from running, and the risk of reinjury is high. The risk of reinjury may be up to 36%, compared to between 1% and 21% risk of initial stress fracture (Hauret et al., 2001). There is some evidence that stress fractures are related to running gait mechanics. In cross-sectional studies, runners who had sustained a stress fracture had higher instantaneous loading rate (ILRZ) and peak tibial shock (PPA) and reduced knee flexion excursion (KEXC). The effect of a previous stress fracture on running mechanics is unknown and could be a factor in the high rate of reinjury in this group.

The aim of this study was to determine whether pre-injury running mechanics are altered following the occurrence and recovery from a lower extremity stress fracture. In addition, impact peak (IPEAK) and braking load rates (ILRY, ALRY) will be examined, as they may also be linked to injury in runners. It was expected that the magnitudes of ILRZ, PPA and KEXC that have been related to stress fracture would be present prior to the injury, and that they would remain the same post injury.

## METHODS

These data are part of an ongoing prospective study of female distance

runners. Currently uninjured adult female runners, typically running at least 20 miles per week, are recruited into a two year longitudinal study. An instrumented gait analysis is performed on entry into the study. Subjects run overground at 3.7m/s in standard laboratory running shoes. Five trials are recorded using a six camera motion capture system at 120 Hz and a force platform and accelerometer at 960 Hz. Three-dimensional kinematics and kinetics are calculated for both lower extremities.

Subjects are then followed monthly for two years. Running mileage and injuries are tracked. All participants who sustain a stress fracture of the lower extremity are asked to return to the laboratory for a second instrumented gait analysis. The post-injury analysis is performed when they have recovered from injury and returned to at least 50% of their pre-injury mileage.

To date, six runners (30±13 y, 24±12 mpw) have sustained a lower extremity stress fracture or tibial stress reaction. A tibial stress reaction is operationally defined as bone pain and tenderness located over a diffuse area of several centimeters. The pain is alleviated by rest and worsens with continued running. Essentially this is the early stage of development of a full stress fracture and will likely progress to fracture if the training load is not removed (Batt et al., 1998). We have included stress reaction in this group as it indicates susceptibility to stress fracture. A control group of 6

uninjured runners matched for age and mileage ( $23 \pm 8$  y,  $26 \pm 1$  mpw) was also included. Comparisons were made between controls and injured runners' pre- and post-injury data. Statistical analyses were not conducted due to the small sample size.

## RESULTS AND DISCUSSION

Using a 15% change as being clinically relevant, several variables showed a notable increase following stress fracture in these runners (Table 1). ILRZ and PPA were higher in the stress fracture group compared to controls prior to injury. In addition, ILRZ and PPA became notably higher post-injury in the fracture group. Since stress fractures are essentially fatigue fractures of the bone, their occurrence relates to the load per cycle and the number of cycles. Increasing either of these factors increases the risk of exceeding the fatigue limit of the tissue. ILRZ and PPA indicate the magnitude of compression loading per cycle, therefore higher values indicate increased risk.

**Table 1:** Changes in selected variables following a lower extremity stress fracture or reaction in female runners (mean  $\pm$  SD).

	CTRL	PRE	POST
ILRZ (BW/s)	97.7	120.20#	146.19*
PPA (g)	5.22	9.10#	10.88*
KEXC (°)	35.5	34.4	32.1
IPEAK (BW)	1.55	1.87#	1.96
ILRY (BW/s)	34.00	39.13#	50.74*
ALRY (BW/s)	7.10	7.04	11.13*

# Greater than 15% difference between control and pre-injury. \* Greater than 15% change pre- to post-injury.

These data suggest that runners who sustain a stress fracture have a more risky gait prior to injury and are adopting an even more risky gait following recovery from stress fracture. This finding may explain the high incidence of reinjury following a lower extremity stress fracture in runners.

Of the additional variables studied, both ILRY and ALRY increased notably following recovery from stress fracture. ILRY was also increased compared to controls in the fracture group prior to injury. These shear loading rates indicate the magnitude of bending loads that the lower extremity is subject to, in addition to the compressive loading that occurs during initial weight acceptance in stance. It has been shown that anterior-posterior bending strength is related to the risk of tibial stress fracture (Milgrom et al., 1989). Therefore, the magnitude of anterior-posterior loading rates may be directly related to stress fracture. The secondary planes of ground reaction force are often overlooked in gait analyses, but these substantial changes indicate that they are worthy of further investigation in relation to stress fracture injuries in runners.

## SUMMARY

Runners who sustain a lower extremity stress fracture have higher lower extremity load rates and shock prior to injury in comparison with controls. Post-injury subjects adopted a more risky gait, with further increases in lower extremity load rates and shock.

These preliminary data suggest that interventions to reduce loading post fracture need to be developed.

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## **Appendix 2**

**Articles in preparation for submission to *Medicine and Science in Sport and Exercise*.**

**1) BIOMECHANICAL FACTORS ASSOCIATED WITH TIBIAL STRESS FRACTURE IN FEMALE RUNNERS.**

**2) RETROSPECTIVE BIOMECHANICAL INVESTIGATION OF ILIOTIBIAL BAND SYNDROME IN COMPETITIVE FEMALE RUNNERS**

## Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners

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## ABSTRACT

**Purpose:** Tibial stress fractures are among the most serious running injuries that limits the ability of the individual to engage in running. The purpose of this cross-sectional study was to determine whether differences in structure and mechanics exist between trained distance runners with a history of prior tibial stress fracture and those who have not sustained a fracture.

**Methods:** Female runners with a rearfoot strike pattern, aged between 18 and 45 years and running at least 20 miles per week, were recruited for this study. Twenty-four subjects with a history of tibial stress fracture (RTSF) and 24 age and mileage matched control subjects with no previous lower extremity bony injuries participated in this study. Kinematic and kinetic data were collected during overground running at 3.35 m/s using a six camera motion capture system, a force platform and accelerometer. Variables of interest were: vertical impact peak; peak vertical force; instantaneous and average vertical loading rate; peak braking force; instantaneous and average loading rate during braking; ankle and knee flexion excursion; leg, ankle and knee stiffness and peak tibial shock. Structural measurements were made during a lower extremity examination (tibial varum) and with tibial x-rays (tibial area moment of inertia). **Results:** The RTSF group had significantly higher vertical and anteroposterior loading rates, tibial shock and knee joint stiffness than the control group. **Conclusion:** These data suggest that tibial stress fractures in runners are related to dynamic biomechanical variables associated with loading during running, and not to lower extremity structural characteristics.

## INTRODUCTION

Running has become one of the most popular fitness activities with approximately 15 million Americans engaged in running as a means of exercise (Novacheck, 1998). Associated with these numbers are increased rates of running-related injuries. Incidence rates have been noted between 57-85% (Lysolm et al, 1987, Watson et al, 1987 & Bovens et al, 1989), depending on the definition of injury and the study population. In many cases, these injuries limit the runner's ability to engage in running, and the overall purpose of the exercise becomes defeated. In addition, the individual's ability to work may also be compromised. By understanding the etiology of specific injuries, it is hoped that preventative measures can be developed.

Stress fractures are among the top 5 injuries cited to account for 50% of all injuries sustained by runners and military recruits (Clement et al., 1981; James et al., 1978; Jones et al., 1983; Kowal, 1980; Pagliano et al., 1980, Reinker et al., 1979). The overall incidence of stress fractures ranges from 1-25% (Bensel et al., 1983; Brudvig et al., 1983; Kowal, 1980; McBryde et al., 1981; Milgrom et al., 1989, Reinker et al., 1979; Zernicke et al., 1993). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (Pester & Smith, 1992). Similarly, the incidence of stress fractures in female college athletes was double that of males at a Division I institution (Arendt et al., 2004). Others have reported an even greater gender bias in stress fracture incidence (Brudvig et al., 1983, Reinker et al., 1979). The tibia is the most common site of stress fractures in runners accounting for between 32 -56% of total stress fractures reported (Bruckner et al., 1996; Giladi et al., 1987; Ha et al., 1991; Matheson et al., 1987; Pester and Smith, 1992; Taunton et al., 1981).

A number of theories exist surrounding the etiology of these fractures. However, it is generally accepted that an imbalance between osteoblastic and osteoclastic activity is involved with resorption rates superceding deposition rates, resulting in a weakened state of the bone. Further cyclical loading results in microtears at the cellular level (stress fracture), which, if untreated, can develop into a complete fracture. It is likely that multiple factors contribute to the occurrence of a stress fracture. Diet, prior fitness level, bony structure and alignment are all factors believed to contribute to one's risk for a stress fracture. However, most authorities also recognize that one's mechanics play an important role in the stresses experienced by the lower extremity.

Bone structure is thought to contribute significantly to the overall risk of tibial stress fractures. This has been shown to be the case in both male military recruits and male runners, but not female runners. Medio-lateral tibial width is smaller in those military recruits who go on to develop a stress fracture (Giladi et al., 1987), and tibial cross sectional area is smaller in runners with a history of stress fracture (Crossley, 1999). The relationship between tibial area moments of inertia and stress fracture has not been determined for female runners. However, tibial cross-sectional area was not linked to the occurrence of tibial stress fracture in a single study of a small group of female runners with a history of stress fracture (Bennell et al., 2004).

Anatomic alignment has also been implicated in the etiology of stress fractures. Matheson et al. (1987) noted that varus malalignment (genu, tibial, subtalar and forefoot varus) was often present in athletes with stress fractures. During running, the body experiences vertical forces of nearly three times body weight. During this compressive loading, a tibia in varus will likely experience greater bending moments as the vertical force vector projects medial to the tibial shaft. This may result in greater susceptibility to stress fractures.

Stress fractures are related to some quantity, or “dose” of loading, where dose may be a measure of some combination of shock, loading rates, peaks and repetitions. Grimston et al (1991) reported significantly higher vertical impact and propulsive forces, greater peak mediolateral forces and greater peak negative anteroposterior forces in female runners with a history of stress fractures compared to those without. Conversely, Bennell et al. (2004) found no difference in peak ground reaction forces between female runners with and without a history of stress fracture. Increased forces would likely result in greater bending moments experienced by the tibia. Furthermore, Hennig et al, (1993) reported that vertical ground reaction force loading rates were strongly correlated ( $r=0.98$ ) to peak tibial accelerations during running. Therefore, if loading rates are increased, it is likely that tibial shock is also increased. Whether the increased loading rates are directly related to strain rates experienced by the bone is yet to be determined.

The total range of motion the lower extremity undergoes during the loading phase of gait may influence the forces experienced by the body. Assuming a given impulse, larger excursions will likely result in lower peak ground reaction forces and possibly lower loading rates. McNitt-Gray et al. (1994) demonstrated this principle by reporting that lower peak ground reaction forces and loading rates were associated with larger hip and knee flexion excursions in controlled landings in gymnasts. These increased excursions may therefore reduce one’s risk for stress fractures. McMahon et al. (1987) have shown that running with exaggerated knee flexion (Groucho running) reduces the effective vertical stiffness of the lower extremity and causes the runner to attenuate more shock between the shank and head, compared to normal running. Conversely, if ankle and knee joint excursions are decreased, greater lower extremity stiffness will likely result. A “stiff” runner has been shown to spend less time in contact with the ground

(Farley and Gonzalez, 1996) and attenuate less shock (McMahon et al., 1987). This may also increase their risk of stress fractures.

The purpose of this cross-sectional study was to determine whether differences in structure and mechanics exist between trained distance runners with a history of a prior tibial stress fracture and those who have not sustained a fracture. We hypothesized that runners who had a prior tibial stress fracture would exhibit increased vertical loading rates, increased impact peak and peak vertical GRF, increased loading rates during braking, increased braking force and increased stiffness, compared to those who have not sustained a fracture. Furthermore, runners who had sustained a tibial stress fracture will exhibit increased tibial acceleration, decreased dorsiflexion excursion and decreased knee flexion excursion. Structurally, they will exhibit increased tibial varum and decreased tibial area moment of inertia.

## METHODS

**Subjects.** Approval for all procedures was obtained from the Human Subjects Review Board of the University of Delaware prior to the commencement of this study. All subjects gave their written informed consent prior to participation in the study. Participants aged between 18 and 45 years who typically ran at least 32 km per week were recruited from local races, running clubs and university cross country teams. Subjects were excluded if they were currently injured, had a history of cardiovascular pathology, had abnormal menses (defined as missing more than three consecutive monthly periods in the last 12 months) or were pregnant or suspected they were pregnant. Twenty-four rearfoot strikers with a history of tibial stress fracture (RTSF: age  $29 \pm 11$  y,  $49 \pm 18$  km per week) and 24 age and mileage matched rearfoot striking control subjects with no previous lower extremity bony injuries (CTRL: age  $26 \pm 9$  y,  $48 \pm 19$  km per week

participated in this study. On entry into the study, the RTSF group had reported a previous tibial stress fracture, that had been confirmed at the time by a medical professional using diagnostic imaging tests (bone scan, MRI or x-ray).

POWER CALC – Bates ref, or which data?

**Kinematic and kinetic measurements.** Lower extremity position data were collected at 120 Hz using a six camera Vicon 512 motion capture system (Oxford Metrics, Oxford, UK). Markers were placed on the lower extremity and pelvic region to enable three-dimensional kinematics to be determined for the stance phase of running (Figure 1). Markers were attached at L5S1, iliac crest and anterior superior iliac spine to track the pelvic segment. Moulded thermoplastic shells with 4 non-collinear markers attached were secured on the posterolateral proximal thigh and posterolateral distal shank. Three markers were attached to the heel portion of the running shoes to approximate rearfoot motion: two marking the vertical bisection of the heel and a third on the lateral side of the heel.

Several additional markers were attached to the subject initially to define the anatomical coordinate systems and inertial parameters of each segment. These markers were removed following the calibration trial. The markers were placed over the greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, first and fifth metatarsal heads and the tip of the toe box. A Bertec force platform (Bertec Corporation, Columbus, OH) synchronized with the motion capture system was used to collect ground reaction force data at 1080 Hz. Additionally, a uniaxial accelerometer (PCB Piezotronics Inc, Depew, NY), also sampling at 1080 Hz, was attached over the anteromedial portion of the distal tibia, as described by (REF –best approximates tibial shock). Running velocity was monitored via two photocells linked to a timer.



Subjects wore standard, neutral laboratory running shoes and ran overground along a 23m runway at a velocity of 3.35 m/s ( $\pm 5\%$ ). Data were collected for a single stance phase as the runner traversed the force plate located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change their gait to target the force platform were discarded. Subjects performed practice trials to ensure that they could maintain a consistent running speed and make contact with the central portion of the force platform without modifying their gait.

Data were processed in Visual 3D (C-Motion, Rockville, MD), using the Joint Coordinate System (Grood and Suntay, 1983) to resolve three-dimensional angles at the ankle and knee. Knee flexion and ankle dorsiflexion excursions were calculated as the range of motion from foot strike to peak flexion. Kinetic data, used in the calculation of joint stiffness, were calculated about Cardan angles embedded in the distal segment. All other variables were calculated using custom LabView (National Instruments Corporation, Austin, TX) programs. Ground reaction force variables (vertical instantaneous and average loading rate (VILR, VALR), impact peak, (IPEAK), active peak (APEAK), anterior-posterior instantaneous and average loading rates during initial braking (BILR, BALR), and peak braking force (BPEAK) were determined. Tibial shock (peak positive acceleration: PPA) was calculated as described by ??REF FROM CARRIE'S THESIS. Leg stiffness was determined using McMahon and Cheng's (1990) spring-mass model. Joint stiffnesses were calculated as the change in joint moment divided by the change in joint angle. These stiffness measures represent the sum of many individual stiffnesses and are often referred to as measures of quasi-stiffness (Latash and Zatsiorsky, 1993). However, for the purposes of this paper the term stiffness will be used.

Sagittal plane joint stiffness was determined for the knee and ankle from foot strike to peak knee flexion (i.e. loading) during stance.

#### STRIKE INDEX – TO CONFIRM RFS/ EXCLUDE MFS, FFS

All variables were determined for each of the five trials per subject, and then averaged within the subject and then across groups. Data were then normalized to 100% stance. Group ensemble curves were then constructed for the purpose of graphical representation.

**Structural measurements** X-rays of both tibiae were taken from anterior and lateral views while standing with feet internally rotated 15° to account for the natural external rotation of the frontal plane of the tibia (Milgrom et al., 1989). A foot template was used to ensure consistency of foot placement between subjects. Tibial area moment of inertia was calculated from measurements made on the x-ray films, according to Milgrom et al. (1989). Tibial varum was measured by an experienced physical therapist as the angle subtended by the bisection of the tibia in the frontal plane and a vertical reference.

**Statistical analysis.** One-tailed independent t-tests were used to test for significant differences between groups, based on the directional hypotheses stated previously. Bonferroni adjustments for multiple comparisons were not made as the hypotheses tested were developed *a priori* and, therefore, should be considered independent of each other (Perneger, 1998). The alpha level was 0.05.

## RESULTS

Both instantaneous and average loading rates were increased in the vertical direction in the RTSF group, compared to the control group (Table 1). Additionally, average loading rate during braking was higher in the RTSF group. However, peak vertical and peak braking forces

were not different between the groups. Knee joint stiffness was increased and knee joint excursion was decreased in the RTSF group (Figure 2). However no differences were noted in overall leg stiffness, ankle joint stiffness or ankle joint excursion between groups (Table 2). The RTSF group also showed a large increase in peak tibial shock compared to controls. Neither of the two structural measures, tibial area moment of inertia and tibial varum, were different between the groups.

## DISCUSSION

We investigated the differences between female distance runners with and without a history of tibial stress fracture. We found no difference in peak vertical or anteroposterior ground reaction force variables. Previous investigations into the relationships between ground reaction force variables and a history of tibial stress fracture also found no difference in peak values (Crossley et al., 1999; Bennell et al., 2004). However, these and our data are in contrast to another study of peak ground reaction force variables that found higher vertical impact, vertical propulsive and braking peaks in a small group ( $n = 6$ ) of runners with history of tibial or femoral stress fracture (Grimston et al., 1991).

Runners who had sustained a tibial stress fracture previously exhibited greater instantaneous and average vertical loading rates, as well as greater average loadrate during braking compared to controls. The risk of tibial stress fracture, which is a fatigue fracture of the bone, may not be related to the magnitude of force directly, but to the rate at which that force is applied to the lower extremity during the loading phase of stance. The fatigue limit of a tissue is related to the type of load applied, its magnitude, rate of application and frequency of application (Bartlett, 1999). When comparing these two groups of runners, the type of load is similar (a

combination of compression and bending) as both groups are rearfoot strikers. The frequency of application is also similar, since the groups were matched for mileage. Differences in load characteristics between the two groups are, therefore, likely to be reflected in the magnitude and frequency of application. We hypothesized that both of these groups of variables would be increased in the stress fracture group. However, our results, and those of Crossley et al. (1999) and Bennell et al. (2004) suggest that the differences lie in the rate of application of force.

Another measure of the load that is applied to the lower extremity is peak positive tibial acceleration, or tibial shock. With the strong correlation reported between vertical loading rates and tibial shock, it was likely that tibial shock was also increased. We found an increase of 22% in instantaneous loading rate and a larger increase of 31% in tibial shock in the stress fracture group. Tibial shock provides a more direct estimate of the load acting on the tibia during the stance phase of running. It may, therefore, be a more sensitive discriminator of runners at higher risk of tibial stress fracture.

The magnitudes of loading rates and peak tibial shock experienced during running are affected by the body's response to the applied load, as well as the magnitude of the load itself. The extreme example of Groucho running (McMahon et al., 1987), in which the runner exaggerates knee flexion, provides a good illustration of this. When running with large amounts of knee flexion, the runner reduces the effective vertical stiffness of the lower extremity. We found an increase in knee joint stiffness, associated with decreased knee flexion excursion in the stress fracture group. This increased stiffness may be a physiological mechanism contributing to the increased loading rates and increased tibial shock in this group. Since the structural measures investigated were not different between the groups, we suggest that dynamic biomechanical

characteristics of running gait contribute to the risk of tibial stress fracture in female distance runners.

McMahon et al. (1987) illustrated how a runner can manipulate aspects of their gait (knee flexion during stance), at least temporarily, which then alters other biomechanical characteristics such as stiffness and shock transmission. This suggests that it may be possible to reduce the risk of tibial stress fracture in distance runners by altering their gait in such a way as to reduce one or more key loading or shock variables that have been associated with this injury. Further studies are needed to determine whether these characteristics of runners with a history of tibial stress fracture exist prior to their injury, rather than developing as a consequence of sustaining the injury. Prior existence of these increased loading rates and shock levels would suggest that they are a cause, rather than an effect, of tibial stress fracture. The case can then be made for reducing the magnitude of these risk factors, when they are high, by manipulating running gait. Reducing the incidence of tibial stress fractures, a common and serious running injury, would enable 'at risk' runners to continue with running as their chosen form of exercise for health and fitness.

In conclusion, based on the results of this study, female runners with a history of tibial stress fracture have higher loading rates and tibial shock during running than those without a previous stress fracture.

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1. TABLE 1. Mean (SD) ground reaction force variables for retrospective tibial stress fracture (RTSF) group and control (CTRL) group.

Ground Reaction Force	RTSF (N = XX)	Control (N = XX)	p value
Vertical Impact peak (BW)	1.84 (0.19)	1.77 (0.34)	0.15
Peak vertical GRF (BW)	2.51 (0.19)	2.53 (0.15)	0.34
Vertical instant LR (BW.s <sup>-1</sup> )*	101.38 (21.31)	83.12 (22.67)	0.003
Vertical average LR (Bw.s <sup>-1</sup> )*	88.38 (19.57)	70.30 (23.61)	0.003
Braking peak GRF (BW)	-0.40 (0.07)	-0.39 (0.05)	0.34
Braking instant LR (BW.s <sup>-1</sup> )	21.92 (7.29)	20.95 (5.36)	0.30
Braking average LR (BW.s <sup>-1</sup> )*	10.55 (5.23)	8.13 (3.00)	0.03

\* significant at  $p \leq 0.05$

Table 2: Mean (SD) joint excursion, stiffness and structural variables for retrospective tibial stress fracture (RTSF) group and control (CTRL) group.

	RTSF (N = XX)	Control (N = XX)	p value
Ankle sagittal excursion angle	20.6 (5.5)	21.1 (4.1)	0.15
Knee sagittal excursion angle*	31.2 (6.2)	33.9 (5.3)	0.06
Vertical leg stiffness	8.8 (1.5)	9.1 (1.5)	0.28
Ankle sagittal stiffness ( $\times 10^{-2}$ )	33.47 (34.87)	29.26 (38.18)	0.36
Knee sagittal stiffness ( $\times 10^{-2}$ )*	5.23 (1.05)	4.69 (0.93)	0.04
Peak tibial shock*	8.74 (2.86)	6.68 (2.21)	0.006
Tibial area moment of inertia	11403 (3224)	12507 (3813)	0.17
Tibial varum	5.7	6.4	0.11

\* significant at  $p \leq 0.05$

Figure 1: Marker placement used to track the movements of the lower extremity during the stance phase of running.

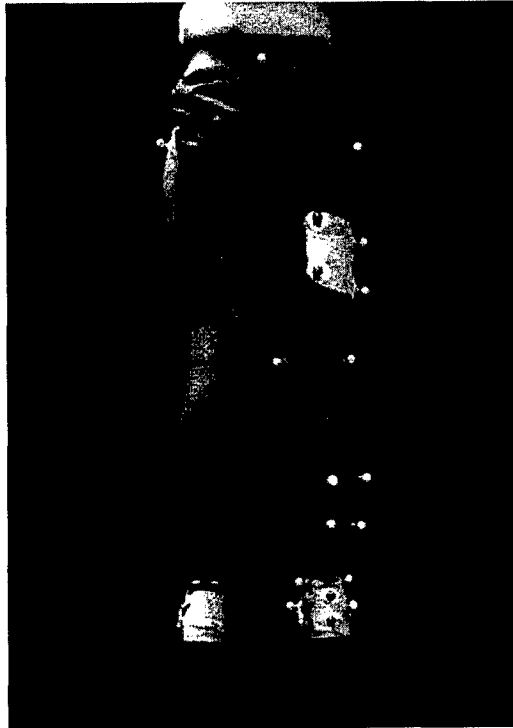
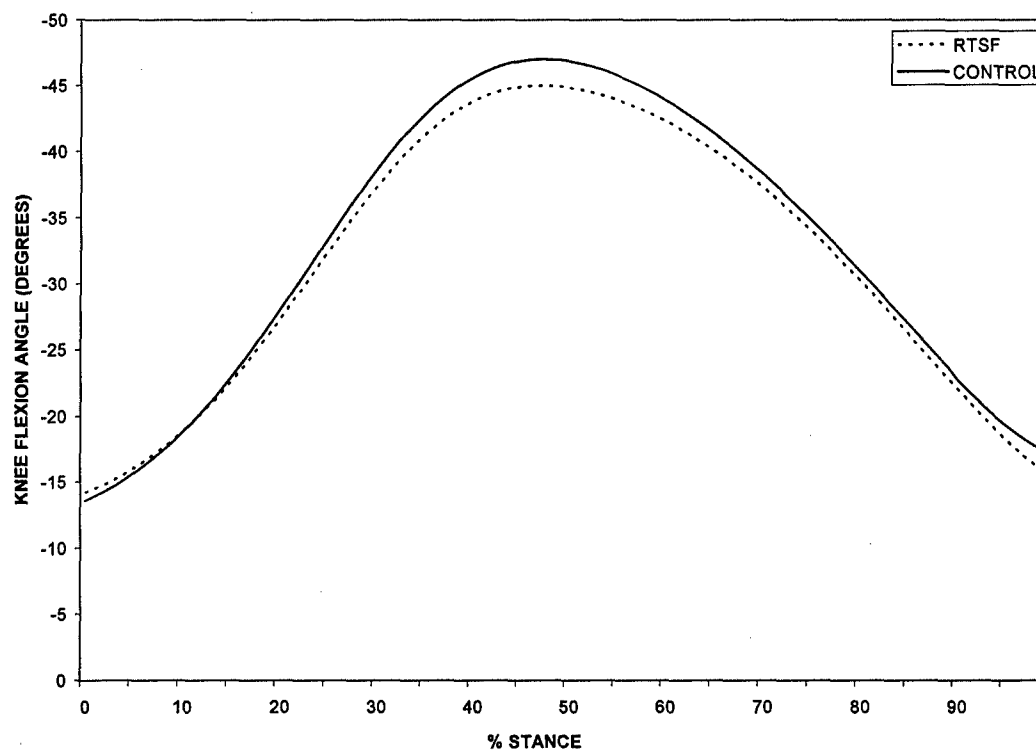


Figure 2. Knee flexion angle during the stance phase of running for retrospective tibial stress fracture (RTSF) group and control (CTRL) group.



# RETROSPECTIVE BIOMECHANICAL INVESTIGATION OF ILIOTIBIAL BAND SYNDROME IN COMPETITIVE FEMALE RUNNERS

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## ABSTRACT

**Purpose:** To examine differences in running mechanics between runners who had previously sustained iliotibial band syndrome (ITBS) and runners with no knee-related running injuries.

**Methods:** The gait mechanics of 22 females who had been diagnosed with ITBS were compared to 22 age, mileage, and limb matched healthy females during running. Comparisons of hip and knee 3-D joint angles, angular velocities, and moments during the stance phase of running gait were made.

**Results:** No significant differences between groups were observed for the frontal plane rearfoot or transverse plane knee or hip variables of interest. The ITBS group exhibited a trend towards greater peak hip internal rotation angle a significantly greater peak hip adduction angle compared to the control group.

**Conclusions:** Female recreational runners who had previously sustained ITBS exhibited greater hip frontal and transverse plane motions during running compared to controls. These data may may explain how, overtime, atypical running mechanics can lead to lower extremity musculoskeletal injuries such as ITBS.

**Key Words:** Iliotibial band syndrome, Running mechanics, Kinematics, Kinetics

## INTRODUCTION

Iliotibial band syndrome (ITBS) is one of the most common injuries runners sustain (Taunton, 2002). Repetitive friction of the ITB over the lateral femoral epicondyle can lead to inflammation, hyperplasia, fibrosis, and mucoid degeneration observed as pain associated with ITBS (Nemeth et al., 1996). Orchard et al. (1996) suggested that the ITB experiences the greatest amount of friction with the lateral femoral epicondyle near 30° of knee flexion which is observed during the first half of the stance phase of running.

The iliotibial band (ITB) functions as an anterolateral knee stabilizer and as a hip abductor (Frederickson et al., 2000). It has been reported that runners with ITBS exhibited significantly weaker hip abductor muscle strength in the affected limb compared to the unaffected limb and healthy controls (Frederickson et al., 2000). The primary adductor of the hip is the gluteus medius, which also acts as an external rotator, and the tensor fascia latae (Moore, 2003). Thus, weakness of these muscles would suggest that runners with ITBS may exhibit greater hip adduction and internal rotation during the stance phase of running.

It has been suggested that excessive rearfoot motion can influence knee mechanics and contribute to running-related injuries such as patellofemoral pain and ITBS (Duffey et al., 2000; Hamill et al., 1999; Williams et al., 2003). Greater amounts of rearfoot motion are likely to influence knee motion due to the coupling that has been shown to occur in the lower extremity (Lundberg, 1989; Inman, 1976). During the first half of the stance phase, the calcaneus everts and the head of the talus internally rotates (Lundberg, 1989; Inman, 1976). The tibia internally rotates with the talus due to the tight articulation of the ankle joint mortise. Therefore, chronic and excessive amounts of rearfoot eversion could result in greater knee internal rotation and potentially be associated with the etiology of ITBS.



Previous studies suggest that the etiology of ITBS may be related, in part, to atypical running mechanics. However, few studies have performed a comprehensive analysis of these variables. Thus, the purpose of this study was to examine differences in running mechanics between female runners who had previously sustained ITBS compared to runners with no knee-related running injuries. It was hypothesized that the ITBS runners would exhibit greater hip adduction and internal rotation, knee internal rotation, and rearfoot eversion peak angles, peak angular velocity and peak joint moments compared to the control group.

## METHODS

### *Subjects*

A priori power analyses ( $\beta=0.20$ ;  $P=0.05$ ) were conducted based on pilot data (Ferber et al., 2003) and a minimum of 14 subjects per group were found to be necessary for statistical significance. The subjects involved in this study ( $n=44$ ) were part of a larger ongoing prospective investigation of female running injuries ( $n=400$ ). As part of the larger study, all previous lower extremity injuries for all participants were recorded. The database was then examined and 22 females who had been diagnosed with ITBS by physician and/or a licensed physical therapist were chosen for analysis for this study. Twenty-two age, mileage, and limb matched females with no previous knee-related musculoskeletal injuries were then chosen for the control group. The age, mean body mass, and body height of the ITBS subjects were 35.47 years (SD 10.35 years), XXkg (SD XXkg), and XXm (SD XXm), respectively and the control subjects were 31.23 years (SD 11.05 years), XXkg (SD XXkg), and XXm (SD XXm), respectively. All subjects were free of any obvious lower extremity malalignments or injuries at the time of data collection. Prior to participation, each subject signed a consent form approved by the University's Human Subjects Compliance Committee.

### *Procedures*

Retro-reflective markers for tracking three-dimensional movement were placed on the thigh, shank, pelvis, and rearfoot (Figure 1). Anatomical markers defining the joint centers were placed over the following locations: bilateral greater trochanters, medial and lateral femoral condyle, medial and lateral malleoli, heads of the 1<sup>st</sup> and 5<sup>th</sup> metatarsals. After a static standing calibration was collected, the anatomical markers were removed and dynamic trials were

collected. Subjects ran along a 25m runway at a speed of 3.65 m/s ( $\pm 5\%$ ) striking a force plate at its center. Running speed was monitored using photoelectric cells placed 2.86 m apart along the runway. Five running trials were collected for the right lower extremity during stance.

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Insert Fig. 1 about here

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#### *Data collection and analysis*

Kinematic data were collected with a passive, 6-camera, 3-D VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK). The cameras were calibrated to a volume of 2.0 m<sup>3</sup> and calibration errors were all below 3 mm. Kinematic data were sampled at 120 Hz and low-pass filtered at 8 Hz with a fourth-order zero lag Butterworth filter. Kinetic GRF data were collected using a force plate (BERTEC Corp, Worthington, OH, USA). GRF data were collected at 960 Hz and low-pass filtered at 50 Hz with a fourth-order zero lag Butterworth filter. Trials were normalized to 100% of stance and five were averaged for each subject.

Visual3D software (NIH Biomotion Laboratory, Bethesda, MD, USA) was used to calculate kinematic and kinetic variables. All lower extremity segments were modeled as a frustra of right cones model and anthropometric data provided by Dempster (1959). The kinematic and kinetic variables of interest were extracted from individual trials.

#### *Statistical design*

The kinematic and kinetic variables of interest were selected from the first 60% of the stance phase of gait and included ankle and knee joint 3D peak angles, peak angular velocities, and peak moments. Specific biomechanical variables of interest were 1) rearfoot peak eversion angle, excursion, and velocity, and inversion moment, 2) knee peak internal rotation angle and velocity and external rotation moment, and 3) hip peak internal rotation angle and velocity and

internal rotation moment, and 4) hip peak adduction angle and velocity and abduction moment. Variables were statistically compared using one-way ANOVAs at a confidence level of 0.05. Tukey post-hoc tests were performed where appropriate.

## RESULTS

Table 1 presents a summary of kinematic and kinetic comparisons of the variables of interest for the ITBS injured and non-injured and the control group's matched limb. No significant differences were observed for the frontal plane rearfoot or transverse plane knee variables of interest (Table 1). No significant differences were observed for transverse plane hip variables although the ITBS group exhibited a trend towards greater peak hip internal rotation angle compared to the control group (Table 1). In the frontal plane, the ITBS group exhibited a significantly greater peak hip adduction angle compared to the control group (Table 1).

Table 1: Mean (SE) and *P*-value for the ITBS non-injured and previously injured limb compared to the control (CON) group for the selected variables of interest.

Joint	Variable of Interest	ITBS Injured	CON	<i>P</i> -value
<b>Rearfoot</b>	Ev Excursion (deg)	13.16 (0.96)	14.00 (1.13)	0.57
	Peak Ev Angle(deg)	9.54 (0.61)	9.19 (0.85)	0.74
	Peak Ev Vel (deg/s)	182.95 (14.36)	216.07 (18.11)	0.16
	Peak Inv Mom (Nm/kg)	-0.16 (0.03)	-01.5 (0.03)	0.69
<b>Knee</b>	Peak Int Rot Angle (deg)	1.39 (1.38)	1.37 (1.40)	0.99
	Peak Int Rot Vel (deg/s)	151.26 (9.42)	163.22 (17.00)	0.54
	Peak Ext Rot Mom (Nm/kg)	-0.09 (0.01)	-0.10 (0.02)	0.50
<b>Hip</b>	Peak Int Rot Angle (deg)	11.60 (3.37)	5.88 (0.92)	0.09
	Peak Int Rot Vel (deg/s)	86.03 (10.51)	105.56 (11.51)	0.22
	Peak Int Rot Mom (Nm/kg)	0.38 (0.02)	0.38 (0.03)	0.97
	Peak Add Angle (deg)	10.98 (1.26)	7.08 (1.03)	0.02 *
	Peak Add Vel (deg/s)	148.31 (12.57)	153.33 (11.17)	0.76
	Peak Abd Mom (Nm/kg)	-1.37 (0.05)	-1.45 (0.06)	0.22

\* indicates CON different than ITBS non-injured limb

## DISCUSSION

The purpose of this study was to examine differences in running mechanics between runners who had previously sustained ITBS and runners with no knee-related running injuries. There is a paucity of literature related to running mechanics and the etiology of ITBS in runners. Of those studies, few studies have comprehensively examined how atypical running mechanics may be related to the etiology of ITBS.

In support of the hypothesis, the ITBS group exhibited a trend towards greater peak hip internal rotation angle and a significantly greater peak hip adduction angle for the previously injured limb compared to the control group. These results support those of Fredrickson et al. (2000) who reported that runners with ITBS exhibited significantly weaker hip abductor muscle strength in the affected limb compared to healthy controls. It seems likely that weakness of the hip adductor muscles (gluteus medius and tensor fascia latae) would result in greater hip adduction and internal rotation during the stance phase of running. It is also possible that repetitive exposure to greater hip adduction and internal rotation may necessitate greater passive restraint from the ITB and, overtime, result in the development of ITBS. However, prospective studies are necessary to better determine the role of excessive hip joint frontal and transverse plane motion and ITBS.

It has been postulated that known differences in structure may predispose females to differences in running mechanics which, over many repetitions, may lead to specific injuries. Female recreational runners twice as likely to sustain ITBS as compared to their male counterparts (Taunton et al, 2002). Ferber et al. (2003) suggested that female recreational runners exhibited a greater peak hip adduction and internal rotation angle compared to male runners possibly as a result of greater hip width to femoral length ratio and greater active hip

internal rotation range of motion, respectively (Horton & Hall, 1989; Simoneau et al., 1998). While not measured in the current study, the greater peak hip adduction and internal rotation angle observed in the ITBS group may be linked to differences in anatomical structure and range of motion compared to the control group. Studies determining how anatomical structure and gait mechanics are necessary to better determine this association.

Contrary to the hypotheses, there were no differences in any rearfoot frontal plane or knee transverse plane variables of interest. Other studies have suggested that greater amounts of rearfoot eversion can lead to increased knee rotation and possibly contribute to the development of certain lower extremity injuries such as ITBS (McClay and Manal, 1997; Nigg et al., 1993; Nawoczenski et al., 1998; Williams et al., 2001). Pilot data based on a group of prospective ITBS injured subjects showed that greater peak rearfoot eversion and knee internal rotation angles were observed compared to healthy controls (Ferber et al., 2003). However, results from the current study suggest that rearfoot and knee mechanics are not different between runners who have previously sustained ITBS and healthy controls.

There are factors which may have influenced the results of this study. The study is retrospective in nature. Therefore, it is difficult to draw conclusions between running mechanics and the etiology of ITBS. Secondly, the ITBS runners were healthy at the time of testing so true differences between the two groups may be masked. Third, it is possible that inclusion of more subjects may have resulted in statistical significance for some of the comparisons. However, a sample size estimate indicated that 22 subjects were sufficient.

In conclusion, female recreational runners who had previously sustained ITBS exhibited a greater peak hip internal rotation and adduction angle for the injured limb compared to the matched limb of the control group. No differences in rearfoot or knee mechanics were observed

between the groups. These data may may explain how, overtime, atypical running mechanics can lead to lower extremity musculoskeletal injuries such as ITBS. However, prospective studies are necessary to better determine the role of gait mechanics and the development of running-related injuries.

## **ACKNOWLEDGEMENTS**

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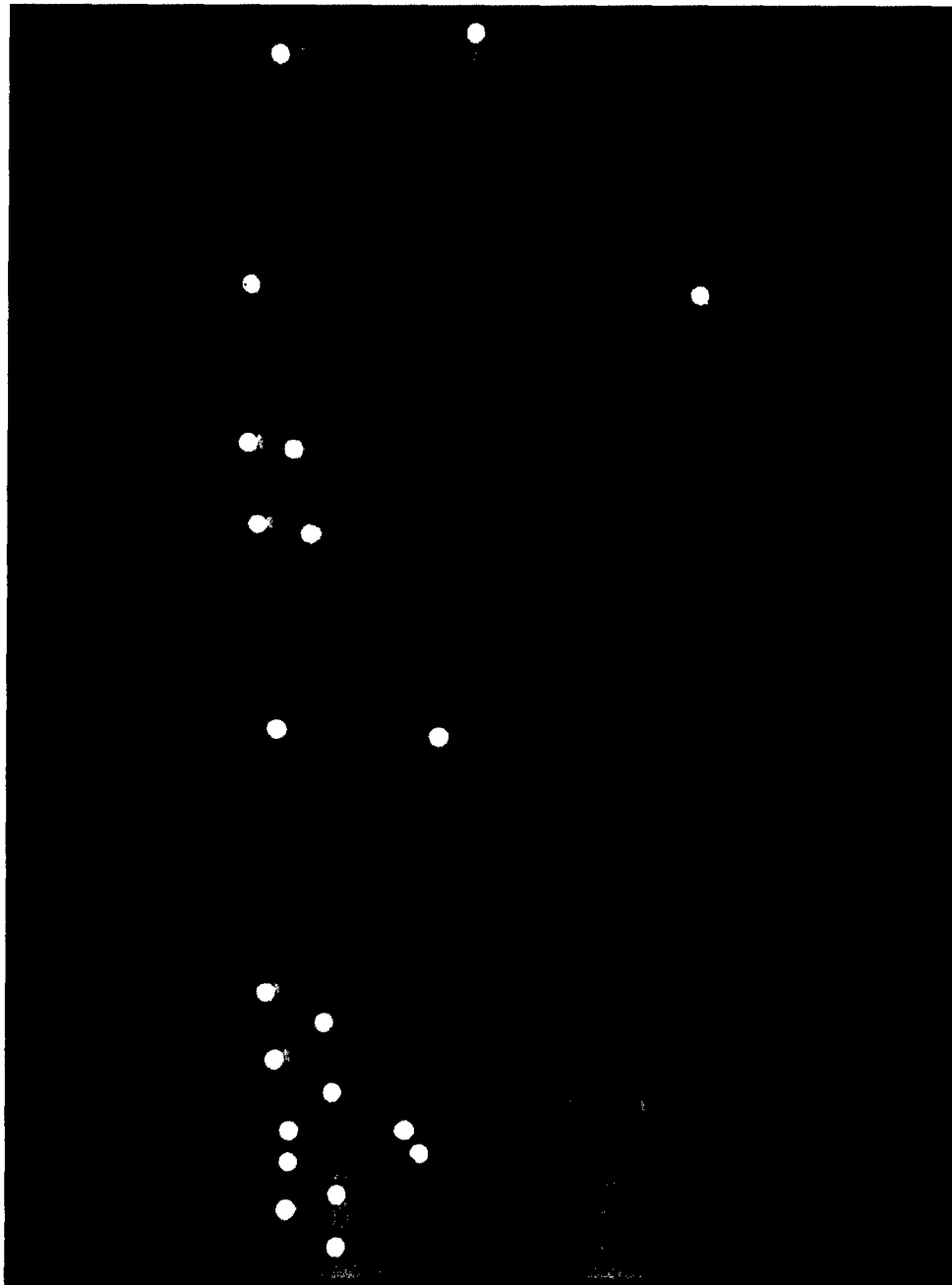


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Figure 1



**Appendix 3**  
**Advertisement Flyer**

# FREE BIOMECHANICAL ANALYSIS



We are looking for Female Distance Runners who meet the criterion below to help better understand the mechanisms involved in Lower Extremity Running Injuries.



◆ As you may know, female runners are at a higher risk of sustaining a lower extremity running injury than their male counterparts.

◆ As a subject you will be making a significant contribution to this area of research and will gain better understanding of your own lower extremity structure and mechanics. You will also receive **\$50.00** upon completion of the study.

## Inclusion Criteria:

- Ages 18-45
- Average 20 miles per week

**Requirements:** One two-hour data collection will occur at the University of Delaware in Newark that includes a lower extremity evaluation by a licensed physical therapist, 3-D motion analysis of your running gait, and an x-ray of your lower extremities.

Please contact Clare Milner at 302-831-4646 or [milner@udel.edu](mailto:milner@udel.edu)

Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>
Running Injury Study	Clare Milner 831-4646	<a href="mailto:milner@udel.edu">milner@udel.edu</a>

## **Appendix 4**

### **Curriculum Vitae for Irene S. McClay**

**Irene S. Davis**  
**Curriculum Vitae**

**PERSONAL**

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Address: 305 McKinly Lab, University of Delaware, Newark, DE 19716  
Phone: (H): (302) 234-0532 (O): (302) 831-4263, (fax): (302) 831-4234  
Email: [mcclay@udel.edu](mailto:mcclay@udel.edu) [www.udel.edu/pt/davis/index.htm](http://www.udel.edu/pt/davis/index.htm)  
SSN: 047-40-3391

**EDUCATION**

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PhD	1990	Pennsylvania State University	Biomechanics
MEd	1984	University of Virginia	Biomechanics
BS	1978	University of Florida	Physical Therapy
BS	1977	University of Mass.	Exercise Science

**EMPLOYMENT**

---

Director of Research, Joyner Sportsmedicine Institute, (6/97 - present)

Development of research within the Joyner Sportsmedicine Institute aimed at advancing the science of sportsmedicine and improving prevention, diagnosis and treatment of sports-related injuries.

Associate Professor, Program in Physical Therapy, University of Delaware. (5/97 - present)

Assistant Professor, Program in Physical Therapy, University of Delaware. (9/89 - 5/97)

Instruction of graduate students in physical therapy. Research in biomechanics with specific interest in lower extremity mechanics and injury. Director, Running Injury Clinic.

Research Assistant, Pennsylvania State University, Center for Locomotion Studies. (8/85 - 6/89)

Responsible for the development and coordination of the Running Injury Clinic and Orthopedic Clinic. Research activities in locomotor biomechanics. Consultant to the Distance Runner's Camp at US Olympic Training Center.

Research and Teaching Assistant, University of Virginia, Rehabilitation Engineering Center. (8/82-8/85)

Research activities in wheelchair ergonomics. Instructor of graduate courses in biomechanics and human dissection. Co-coordinator of the Arts and Science of Sports Medicine Conference held annually at the University of Virginia (6/84, 6/85)

Physical Therapist, Blue Ridge Rehabilitation Associates, Charlottesville, VA (1/83 - 7/85)

Part time home health and private practice physical therapy.

Physical Therapist, Woodrow Wilson Rehabilitation Center, Fishersville, VA (2/79 - 6/82)  
Patient treatment, supervision of physical therapy students, inservice training and  
Coordinator of the Amputee Clinic. Instructor in continuing education course in  
Management of the Spinal Cord Injured Patient.

### Grants

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Gender Bias and ACL Injuries: Risk Factors and Interventions (in review). R01 submitted  
to the National Institutes of Health for **\$1.70 million** for 5 years.

Gait Retraining in Runners (in review). R03 submitted to the National Institutes of Health  
(NIAMS) for **\$150,000** for 2 yrs. (Score - 168)

The Effect of Wedged Foot Orthoses on Lower Extremity Mechanics and Function in  
Patients with Knee Osteoarthritis. National Institutes of Health (COBRE Grant)  
**\$932,815** for 5 years beginning 02/2002.

A Comparison of Custom and Semicustom Foot Orthotic Devices on Lower Extremity  
Mechanics and Comfort. The Pauline Marshall Research and Education Foundation,  
**\$15,000** for one year grant period beginning 9/2001 .

Biomechanical Factors Associated with the Etiology of Stress Fractures in Runners. The  
Department of the Army. **\$1.05 million** for 5 yr grant period beginning 9/2000.

2 Doctoral Scholarship. **\$20,000**. Joyner Sportsmedicine Institute, 1998, 1999, 2000, 2001;  
**\$36,000** for 2002. 2003

Undergraduate Summer Scholarship. **\$4,000**. Joyner Sportsmedicine Institute, 1997 and  
1998, 1999, 2000, 2001

A Comparison of Four Methods to Obtain a Negative Impression of the Foot, **\$3,250**, Foot  
Management, Inc, 1998-1999

The Effect of Different Orthotic Devices on Lower Extremity Mechanics of Rearfoot and  
Forefoot Strikers, **\$3,500**. Foot Management, Inc, 1999-2000.

The Effect of the Protonics System on Patellar Alignment and Gait in Patients with  
Patellofemoral Joint Pain. **\$18,000**. Funded by Inverse Technology, 1998-1999

Clinical Efficacy of the Protonics System in Patients with Patellofemoral Joint Pain. **\$3,000**.  
Funded by Inverse Technology, 1998-1999

A Comparison of Strengthening vs. Orthotics on Pronation and Pronation Velocity.  
Funded by the Physical Therapy Foundation **\$60,000**, 1993-1995

Lower Extremity Mechanics and Injury. Funded by the Whitaker Foundation **\$180,000**,  
1993-1996.



- The Relationship between Subtalar Joint Axis Orientation, Joint Motion and Injuries in Runners. Funded by the Biomedical Research Support Grant. \$2550, 1992
- The Relationship between Subtalar Joint and Knee Joint Motion in Runners. Funded by the University of Delaware Research Foundation. \$16,000, 1990.
- A Comparison of Patellofemoral 3-D Kinematics in Runners with and without Patellofemoral Pain. Doctoral Dissertation. Foundation for Physical Therapy. \$8500, 1988.

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#### In Review

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- McRory, JL, Quick, NE, Shapiro, R, Ballantyne, BT, Ireland, ML, and Davis, I** (2004) The Effect of a Single Treatment of the Protonics System on Lower Extremity Kinematics during Gait and the Lateral Step Up Exercise. (in review) *Gait and Posture*.
- Dierks, T and McClay Davis, I** (2004). Discrete and continuous joint coupling measures in recreational runners. (in review) *Medicine and Science in Sport and Exercise*
- Denton, J, Willson, J, Ballantyne, B and McClay Davis, I** (2004). Effect of the Protonics brace system in patients with patellofemoral pain syndrome. (in review) *Journal of Orthopedic and Sports Physical Therapy*
- Deleo, A, Dierks, McClay Davis, I** (2004) A comparison of semi-custom and custom orthoses on rearfoot control and comfort. (in review) *J. Ortho. Sports PT*
- Pantano, KJ, White, SC, Gilchrist, IA, Leddy, J, and Davis, S** (2004) Differences in Peak Knee Valgus Angles between Individuals with High and Low Q-angles During a Single Limb Squat. (in review) *Clin Biom*

#### Abstracts

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- Milner, C, Davis, I and Hamill, J (2004). "Is free moment related to tibial stress fractures in runners?". To be presented at the American College of Sportsmedicine Meeting, Indianapolis, IA, June, 2004.
- Pollard, C, Heiderscheidt, B, Davis, I and Hamill, J. "Influence of Gender on Lower Extremity Segment and Joint Coordination During an Unanticipated Cutting Maneuver." To be presented at the American College of Sportsmedicine Meeting, Indianapolis, IA, June, 2004
- Willson, J, Ireland, ML, and Davis, I (2004). "The influence of lumbopelvic strength on lower extremity performance." To be presented at the American College of Sportsmedicine Meeting, Indianapolis, IA, June, 2004
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- Dierks, TA and McClay Davis, I. Discrete and continuous joint coupling during running. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, 2003.

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- Ireland, ML, Ballantyne, BT, Little, K and McClay, IS.** A Radiographic Analysis of the Relationship between the Size and Shape of the Intercondylar Notch and Anterior Cruciate Ligament Injury Presented at the ACL Research Retreat, Lexington, KY, April, 2001
- Shapiro, R, Yates, J, McClay, I, and Ireland, ML.** Male-Female Biomechanical Differences in Selected Landing Maneuvers. Presented at the ACL Research Retreat, Lexington, KY, April, 2001

- Laughton, CA, **McClay, IS**, Hamill, J. Effect of Orthotic Intervention and Strike Pattern on Tibial Shock in Runners. Presented at the International Society of Biomechanics, Zurich, Switzerland, July, 2001
- McClay, IS**, Hughes, MA, Laughton, CA, Gupta, R. Effect of Soft Orthotics on Tibial Shock and Rearfoot Motion. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Manal, KT & **McClay, IS** Errors in Estimating Tibial Translation during Natural Cadence Walking: Bone vs. Skin Mounted Tracking Markers. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Laughton, CA, **McClay, IS**, & J. Hamill. Effect of Foot Orthoses and Strike Pattern on Rearfoot Motion. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Ballantyne, BT, Leetun, D, Ireland, ML, & **McClay, IS**. Gender differences in core stability as measured by trunk and hip performance Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- McCrory, JL, Quick, NE, Ballantyne, BT & **McClay, IS**. Effect of a Resistive Dynamic Knee Orthosis on Muscle Activations During the Lateral Step Up. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Laughton, CA and **McClay, IS**. Relationship between Loading Rates and Tibial Accelerometry in Forefoot Strike Runners. Presented at the Annual American Society of Biomechanics Mtg, Chicago, IL, July, 2000
- Williams, DS and **McClay, IS**. Lower Extremity Stiffness in Runners with High and Low Arches. Presented at the Annual American Society of Biomechanics Mtg, Chicago, IL, July, 2000.
- Manal, KT, **McClay, IS**, Richards, J and Stanhope, SJ. Effect of Marker Placement on Knee Joint Moments. Presented at the Canadian Society of Biomechanics Mtg, Montreal, July, 2000.
- Hamill, J, Heidersheid, B, **McClay, IS**, Li, L. Influence of Strike Pattern on Lower Extremity Stiffness in Runners. Presented at the Canadian Society of Biomechanics Mtg, Montreal, July, 2000.
- Williams, DS and **McClay, IS**. Injury Patterns in Runners with Pes Cavus and Pes Planus. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.
- Sahte, V, Ireland, ML, Ballantyne BT and **McClay, IS**. Acute Effect of the Protonics System on Patellofemoral Alignment. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.



- Ott, S, Ireland, ML, Ballantyne, BT and **McClay, IS**. Gender Differences in Functional Outcomes following ACL Reconstruction. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.
- Williams, DS, **McClay, IS** & Laughton, CA. A Comparison of between day Reliability of Different Types of Lower Extremity Kinematic Variables in Runners. Presented at the American Society of Biomechanics, October, 1999, Pittsburgh, PA.
- McClay, IS**, Williams, DS & Laughton, CA. Can Gait be Retrained to Prevent Injury in Runners? Presented at the American Society of Biomechanics, October, 1999, Pittsburgh, PA.
- McClay, IS**, Williams, DS and Baitch, S. The Effect of the Inverted Orthotic on Lower Extremity Mechanics. Presented at the International Society of Biomechanics Mtg, August, 1999, Calgary, Canada
- McClay, IS**, & Williams, DS. Structure and Mechanics of Injured Twin Runners. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.
- Wills, J & **McClay, IS**. Epidemiology of Extreme Sports. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.
- Crook, S, Ballantyne, BT & **McClay, IS**. Reliability of a Functional Assessment Tool. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.
- Laughton, CA, **McClay, IS** and Williams, DS. A Comparison of Methods of Obtaining a Negative Impression of the Foot. Presented at the National APTA Conference, Washington, DC, June, 1999.
- Williams, DS, **McClay, IS**. Reliability and Validity of Arch Characterizing Measurements. Presented at the Combined Sections Mtg of the APTA, Seattle, WA, February, 1999.
- McClay, IS**, Williams, DS, and Manal, KT. Lower Extremity Mechanics of Runners with a Converted Forefoot Strike Pattern. NACOB, Chicago, IL, 1998
- Manal, KT, **McClay, IS** et al. A Comparison of Surface Mounted Markers and Attachment Methods in estimating Tibial Rotations during Walking. Am. Soc. Biom. Mtg., Clemson, SC, Oct, 1997
- McClay, IS** The Relationship between Lower Extremity Mechanics and Injury in Runners to be presented at the Whitaker Conference, Utah, August, 1996.
- McClay, IS** & Manal, KT A Comparison of Rearfoot and Knee Kinematics during Running between Excessive Pronators and Normals. Presented at the Canadian Orthopedic Research Society Meeting, Quebec City, May, 1996.

- McClay, IS & Manal, KT** Lower Extremity Kinematic Comparisons between Forefoot and Rearfoot Strikers. Presented at the American Society of Biomechanics Meeting, Stanford, CA August, 1995.
- McClay, IS & Manal, KT** Lower Extremity Kinetic Comparisons between Forefoot and Rearfoot Strikers. Presented at the American Society of Biomechanics Meeting, Stanford, CA August, 1995.
- McClay, IS & Manal, KT** Coupling Parameters in Runners who Pronate and Normals. Presented at the American Society of Biomechanics Meeting, Columbus, Ohio, November, 1994.
- McClay, IS & Manal, KT** (1995). A Comparison of Two- and Three-dimensional Lower Extremity Kinematics during Running between Pronators and Normals. (Presented at the American Society of Biomechanics Meeting, Columbus, Ohio, November, 1994.
- McClay, IS, Cavanagh, PR, Sommer, HJ, & Kalenak, A:** "Three-Dimensional Kinematics of the Patellofemoral Joint during Running". Proceedings of the American Society of Biomechanics Meeting, October, 1991, Tempe, AZ.
- McClay, IS, Cavanagh, PR, Sommer, HJ, & Kalenak, A:** "The Effect of Orthotic Treatment on Tibiofemoral and Patellofemoral Joint Kinematics". *Physical Therapy*, 71(6):S46-7, 1991.
- McClay, IS, Cavanagh, PR, Sommer, HJ, Woltring, HJ, & Kalenak, A:** "Three-Dimensional Angular Kinematics of the Tibiofemoral Joint During Running". Proceedings of the International Symposium on 3-D Analysis of Human Movement, Montreal, July, 1991.
- Cavanagh, PR, Robinson, JR & McClay, IS:** "Biomechanical Perspective of Stress Fractures in Professional Basketball Players". *Med Sci Sport and Exercise* 22:(2) S104, April, 1990.
- Woltring, HJ, McClay, IS, & Cavanagh, PR:** "3-D Photogrammetric Camera Calibration without a Calibration Object." Abstract published in the Proceedings of the International Society of Biomechanics Meeting, Los Angeles, CA, June, 1989.
- McClay, IS, Cavanagh, PR, & Kalenak, A:** "Biomechanical Evaluation of the Injured Runner" Abstract published in the Proceedings of the East Coast Gait Conference, November, 1987.
- Brubaker, CE, McClay, IS, & McLaurin, CA:** "Effect of Seat Position of Propulsion Efficiency." Proceedings of the 2nd International Conference on Rehabilitation Engineering, 1984, pp. 134-138.
- Brubaker, CE, McClay, IS, & McLaurin, CA:** "The Effect of Mechanical Advantage on Lever Propulsion Efficiency". Proceedings of the 6th Annual Conference on Rehabilitation Technology, 1983, pp. 122-124.

## SELECTED INVITED PRESENTATIONS

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- "Is there a right way to run? Relationships between mechanics and injury" Presented at the Graduate Research Symposium, Penn State University, January, 2004
- "A Research Update on Orthotic Intervention" Presented at the Research Symposium at the Temple University College of Podiatric Medicine, December, 2003
- "Foot and ankle case studies in runners" Presented at the Research Symposium at the Temple University College of Podiatric Medicine, December, 2003
- "Is there a right way to run? Relationships between mechanics and injury" Presented at the National Congress of Sports Medicine in Stavanger, Norway, November, 2003.
- "The Role of Core Stability in Lower Extremity Injuries" Presented at the University of MA seminar series, Amherst, MA, November, 2003.
- "Comparison of Comfort and Rearfoot Control between a Semicustom and Custom Foot Orthoses" Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Las Vegas, NV, December 2003.
- "Biomechanical Considerations for Various Types of Foot Orthoses" Presented in the minisymposium titled "Clinical and Biomechanical Efficacy of Foot Orthoses" at the American College of Sports Medicine Mtg in San Francisco, CA, May, 2003.
- "Influence of Foot and Ankle Mechanics of Patellofemoral Joint Dysfunction: A Ground Up Biomechanical Perspective. Presented in the minisymposium titled "The Influence of Lower Quarter Mechanics on Patellofemoral Joint Dysfunction" at the American College of Sports Medicine Mtg in San Francisco, CA, May, 2003.
- "Case Studies in the Injured Runner" Presented at the Medical Aspects of Sports Medicine Mtg, University of Delaware, March, 2003.
- "Evidence for the Effect of Foot Orthoses on Lower Extremity Mechanics" Presented at Temple University College of Podiatric Medicine. February, 2003
- "The Relationship between Structure and Function in the Foot and Ankle". Presented at the Foot Management Inc. Mtg, Ocean City, MD, October 2002
- "Normal and Abnormal Gait" Presented at the Foot Management Inc. Mtg, Ocean City, MD, October 2002
- "The Effect of the Inverted Orthotic on Lower Extremity Mechanics in Patients with Patellofemoral Joint Pain. Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Montreal, Canada, October 2002.

- "Structural Deformities of the Foot: Assessment and Clinical Implications" Presented at the National Athletic Trainers Association Mtg, Dallas, TX, June, 2002
- "Running Mechanics and Injury" Presented at the National Athletic Trainers Association Mtg, Dallas, TX, June, 2002
- "The Role of Core Instability in Lower Extremity Injuries" Symposium: ACL Injuries and the Gender Bias. Presented at the American College of Sports Medicine Mtg in St. Louis, May, 2002.
- "Biomechanical Case Studies in Running Injuries" Symposium: Evidence for injury mechanisms in runners. Presented at the American College of Sports Medicine Mtg in St. Louis, May, 2002.
- "The Application of Biomechanics to Sports Medicine: Focus on Running Injuries" **Keynote lecture** at the Midwest Student Biomechanics Symposium, Normal, IL, March, 2002.
- "Core Instability and Lower Extremity Mechanics: Implications for Injury." Presented at the Combined Sections Meeting of the APTA, Boston, MA, February, 2002.
- "An Update on the Mechanics behind the Success of Orthotic Intervention" Presented at Temple University School of Podiatric Medicine research seminar series, Philadelphia, PA, February 2002.
- "An Update on Orthotic Research: What do Orthotics do?" Presented at the Biokinesiology Graduate Research Seminar Series at the University of Southern California, Los Angeles, CA, November, 2001.
- "The Effect of the Inverted Orthotic on Lower Extremity Mechanics: An Update" Presented at the Prescription Foot Orthotic Laboratory Association Annual Meeting, Miami, FL, November, 2001
- "How Do Foot Orthotic Devices Influence Lower Extremity Mechanics. Presented at the Prescription Foot Orthotic Laboratory Association Annual Meeting, Miami, FL, November, 2001
- "Selected Case Studies in Running Injuries" Presented at the Combined Sections Meeting of the APTA, San Antonio, TX, Feb, 2001.
- "Developing Standards in Epidemiological Research" Presented at the National ACSM Mtg in Indianapolis, June, 2000
- "Lower Extremity Mechanics and Injury Patterns in High and Low Arch Runners". Keynote lecture presented at the Foot and Ankle Research Retreat, Annapolis, MD, May, 2000
- "Effect of the Inverted Orthotic on Rearfoot and Knee Mechanics" Presented at the 4th Annual John Weed Seminar, Palm Springs, CA, March, 2000 and the PFOLA meeting in Vancouver, BC, November 2000

- "Influence of foot, knee and hip coupling on patellofemoral mechanics" Symposium at the Combined Sections Meeting of the APTA, New Orleans, LA, February, 2000 and at the National ACSM Mtg in Indianapolis, June, 2000, and the Arts and Science of Sports Medicine, Charlottesville, VA, June, 2000.
- "Visual Gait Analysis in Runners" Presented at the Arts and Science of Sports Medicine, Charlottesville, VA, June, 2000.
- "Injury Mechanisms in Runners" Keynote speaker at the Fifth IOC Congress on Sport Sciences, Sydney, Australia, November, 1999
- "Clinical Gait Analysis" Keynote speaker at the Fifth IOC Congress on Sport Sciences, Sydney, Australia, November, 1999.
- "Risk Factors in Anterior Cruciate Ligament Injuries" Clinical Colloquium presented at the National ACSM Mtg, in Seattle, WA, June, 1999
- "Problem Solving the Injured Runner" Clinical Colloquium presented at the National ACSM Mtg, in Seattle, WA, June, 1999
- "Coupling between the Foot and the Knee in Runners" Presented at Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, October, 1999
- "Biomechanics of the Knee" Presented at Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, October, 1999
- "Physical Therapist to Marathoner - A Classical Tale of Overuse." Presented at the Case Conference Seminar at the Annual Conference of the American Physical Therapy Association, Minneapolis, MN, June, 1998
- Eugene Michels Research Forum - "Instrumented versus Visual Gait Analysis in Clinical Assessments" Presented at the Combined Sections Mtg in Dallas, TX, Feb., 1997
- "Biomechanical Differences between Forefoot and Rearfoot Strikers" presented at the Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, Nov. 1996.
- "Plantar Fasciitis: A Case Study" Presented at the Case Conference Seminar at the Annual Conference of the American Physical Therapy Association, Minneapolis, MN, June, 1996.
- "The Use of Motion Analysis in Physical Therapy". University of PA, Philadelphia, October, 1995.
- "The Patellofemoral Joint - Implications of the study of three-dimensional kinematics". Grand Rounds, Dept. of Orthopedic Surgery, Hershey Medical Center, January, 1995.
- "What is Clinical Research". Keynote Address at Research Symposium, Shenandoah University, April, 1994 .

- "Research in Foot and Ankle Biomechanics". Presented at the Combined Sections Meeting of the American Physical Therapy Association, New Orleans, LA, February, 1994
- "Biomechanical Assessment of Gait" Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1993
- "Closed Kinetic Chain Activities for the Foot and Ankle" Presented at the Foot and Ankle Seminar for HealthSouth in Orlando, FL, February, 1993, Phoenix, AZ, March, 1993, St. Louis, MO, April, 1993 and for Foot Mgt, Inc in Ocean City, MD in October, 1994 and April, 1996.
- "Normal Structure and Gait". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1992, and at the Symposium on the Biomechanics of the Lower Extremity, NATA, Denver, CO, February, 1992.
- "Abnormal Structure and Gait". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1992, and at the Symposium on the Biomechanics of the Lower Extremity, NATA, Denver, CO, February, 1992 and for Foot Mgt, Inc in Ocean City, MD in October, 1994 and April, 1996.
- "The Biomechanical Evaluation of the Injured Runner". Presented at the Medical Symposium of the Penn Relays, April, 1992, The Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1998 and the East Coast Gait Conference, Bethesda, Md, November, 1997
- "Biomechanics of the Foot and Ankle". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1991
- "Relationship between Mechanics and Running Injuries". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1991.
- "Anatomy and Biomechanics of the Patellofemoral Joint". Presented at the Sports Physical Therapy Meeting, Orlando, Fla. December, 1990
- "Relationship between Structure and Function in Patellofemoral Disorders". Presented at the Sports Physical Therapy Meeting, Orlando, Fla. December, 1990
- "Normal and Abnormal Running Mechanics". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va. June, 1990
- "Biomechanical Perspective of Stress Fractures in Professional Basketball Players". Presented at the Annual Meeting of the NBA Physicians, West Palm Beach, FL, November, 1988.
- "The Biomechanics of Patellofemoral Disorders". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1988.
- "Biomechanical Profile of Elite Woman Distance Runners". Presented at the Dogwood Festival Pre-race Conference, Atlanta, GA, July, 1988.

## HONORS

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Fellow, American College of Sports Medicine	2001
Summa Cum Laude Graduate, The Penn State University	1990
Physical Therapy Foundation Scholar	1988
Recipient of Zipser Scholarship, The Penn State University	1988
Outstanding Masters Student Award, University of Virginia	1984
Nominee for Mary McMillan Scholarship Award, APTA	1978
Magna Cum Laude Graduate, University of Florida	1978
Magna Cum Laude Graduate, University of Massachusetts	1977

## PROFESSIONAL ACTIVITIES

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<b>Societies</b>	American Society of Biomechanics Abstract reviewer, Annual ASB Mtg, Chicago, IL, July 2000 Membership Committee (1997-2001) Scientific Committee for the Third International Symposium on 3-D Analysis of Human Movement, Stockholm, Sweden, 1994 American College of Sports Medicine, Fellow American Physical Therapy Association (APTA) Orthopedic and Research Sections Member Chairperson of Research Committee of the Foot and Ankle Special Interest Group (1997-present) International Society of Biomechanics
<b>Advisory</b>	Invited Participant to the "Working Conference on Gait Analysis in Rehabilitation Medicine" National Institutes for Health, September, 1996 Medical Consultant for Runners World (1995-present)
<b>Ed. Board</b>	Clinical Biomechanics (1999-present) Journal of Orthopedic and Sports Physical Therapy (1996-1997) Journal of Applied Biomechanics (1997-1999)
<b>Reviewer</b>	Journal of Biomechanics Medicine and Science in Sports and Exercise Foot and Ankle, International Journal of the American Podiatric Medical Association Journal of Applied Biomechanics
<b>Other</b>	Organizing Chair for Research Retreat - Measurement of Foot Motion: Forward and Inverse Dynamic Models, University of Southern California, Los Angeles, CA, April, 2004 Organizing Chair for Research Retreat - ACL Injuries: The Gender Bias. Lexington, KY, April 2001, 2003

Organizing Chair for Research Retreat - Static and Dynamic Classification of the Foot. Annapolis, MD, May, 2000.

Member, Organizing Committee, Joyner Sportsmedicine Institute National Sportsmedicine Conference, Hilton Head, SC (1996-1999)

Doctoral Research Advisory Committee (grant reviews), American Physical Therapy Association (1995-1997)

**Licensure**      Licensed Physical Therapist, State of Delaware



**Appendix 5**  
**Curriculum Vitae for Joseph Hamill**

## CURRICULUM VITAE

**Joseph Hamill**

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Professor and Chair  
Department of Exercise Science  
Director, Biomechanics Laboratory  
University of Massachusetts Amherst  
and  
Professor  
Neuroscience and Behavior Program  
University of Massachusetts Amherst

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**BUSINESS ADDRESS:** Biomechanics Laboratory  
Department of Exercise Science  
University of Massachusetts  
Amherst, MA 01003  
(413) 545-2245  
(413) 545-2906 Fax  
jhamill@excsci.umass.edu

**PERSONAL DATA:** Date of Birth: 3/3/46  
Height: 5' 9"  
Weight: 180 lbs  
Citizenship: U.S.

### **EDUCATION**

1967	Teaching Certificate	Lakeshore Teacher's College, Toronto, Canada
1972	B.A.	York University, Toronto, Canada
1977	B.S. (magna cum laude)	Concordia University, Montreal, Canada
1978	M.S.	University of Oregon, Eugene, Oregon
1981	Ph.D.	University of Oregon, Eugene, Oregon

Undergraduate Areas of Study: Political Science  
General Science

Graduate Area of Study: Biomechanics

## **RESEARCH INTERESTS**

Mechanics of lower extremity function  
Mechanical Analysis of normal and pathological gait.  
Modeling the lower extremity in gait.  
Optimality criteria in human locomotion  
Dynamical Systems

## **EMPLOYMENT EXPERIENCE**

1981-1982	Post-doctoral Fellow Biomechanics Laboratory, University of Oregon
1982-1985	Assistant. Professor (Biomechanics) Department of Physical Education, Southern Illinois University
1985-1986	Assistant Professor (Biomechanics) and Graduate Program Director Department of Physical Education, Southern Illinois University
1986-1988	Assistant Professor (Biomechanics) Department of Exercise Science, University of Massachusetts
1989-1995	Associate Professor (Biomechanics) and Graduate Program Director Department of Exercise Science, University of Massachusetts
1990-1995	Adjunct Professor Department of Medicine, University of Massachusetts Medical Center
1995-1996	Associate Professor (Biomechanics) and Department Chair Department of Exercise Science, University of Massachusetts
1996-	Professor (Biomechanics) and Department Chair Department of Exercise Science, University of Massachusetts

## **RESPONSIBILITIES OF PRESENT POSITION**

Department Chair  
Director of the Biomechanics Laboratory  
Teach graduate and undergraduate courses in Biomechanics  
Advise undergraduate and graduate students  
Chair graduate theses and dissertations in the Department  
Conduct research in the area of Biomechanics  
Secure external funding for the Biomechanics Laboratory

## TEACHING RESPONSIBILITIES

### At Southern Illinois University

#### Undergraduate

P.E. 302

P.E. 370

Kinesiology for Physical Therapy  
Tests and Measurements

#### Graduate

P.E. 511

P.E. 512

P.E. 505A

P.E. 505B

P.E. 505C

P.E. 561

Mechanical Analysis  
Biomechanics of Sport  
Biomechanics Instrumentation  
Computer Applications  
Biomechanics of the Musculo-skeletal System  
Doctoral Seminar

### At University of Massachusetts

#### Undergraduate

Ex Sc 300

Ex Sc 305

Ex Sc 304

Ex Sc 311

Ex Sc 474

Writing Seminar for Exercise Science  
Kinesiology  
Human Anatomy  
Anatomy of Human Motion  
Measurement and Evaluation Theory

#### Graduate

Ex Sc 531

Ex Sc 611

Ex Sc 732

Ex Sc 892

Ex Sc 895

Mechanical Analysis of Human Motion  
Introduction to Research  
Advanced Biomechanics  
Doctoral Seminar  
Clinical Biomechanics Seminar

## UNIVERSITY SERVICE

### Department Committees

Master's Thesis Review Committee, 1982-1983

Comprehensive Examination Review Committee, 1983-1984

Chair, Graduate Faculty, 1982-1986

Chair, Search Committee for Department Chairperson, 1986

Graduate Committee, 1986-

Telecommunications Committee, 1988-1990

Chair, Department Personnel Committee, 1994-1995

Chair, Motor Control Search Committee, 1994-1995

### College Committees

College Computer Advisory Committee, 1982-1986

School Personnel Committee, 1994-1995

School Executive Committee, 1995-

Member, School Development Officer Search Committee, 1997.  
University Committees  
Graduate Council, 1991  
Recruitment and Retention Committee, 1991-92  
Research Council, 1992-1995  
Life Sciences Institute Advisory Council, 2003-

## **PROFESSIONAL ORGANIZATIONS**

American Alliance for Health, Physical Education, Recreation and Dance  
Biomechanics Academy of the Research Consortium  
International Society of Biomechanics  
Canadian Society of Biomechanics  
American Society of Biomechanics  
American College of Sports Medicine  
New England College of Sports Medicine  
International Society of Biomechanics in Sport  
ASTM

## **RESEARCH AFFILIATIONS**

Scientific Advisory Board, Rockport Walking Institute, 1986-1992.  
Scientific Advisory Board, LifeFitness, Inc., 1993-  
Scientific Advisory Board, USA Field Hockey, 1995-1998  
USA Volleyball Sports Medicine and Performance Commission's Resource Advisory Committee, 1996-1999

## **ACADEMIC HONORS**

Fellow, Research Consortium of the AAHPERD, 1984  
Fellow, American College of Sports Medicine, 1986  
Fellow, American Academy of Kinesiology and Physical Education, 1997

## **OFFICES IN PROFESSIONAL ORGANIZATIONS**

1. Chair-elect, Kinesiology Academy, 1990-91.
2. Board Member, International Society of Biomechanics in Sports, 1992-94.
3. Chair, Biomechanics Interest Group of the American College of Sports Medicine, 1996-97.
4. Member-at-large, Executive Committee of the New England Chapter of the American College of Sports Medicine, 1995-1997.

5. Board Member, International Society of Biomechanics Technical Group on Footwear, 1998-2000.
6. Member, Credentials Committee, American College of Sports Medicine, 2000-2003.
7. Member-at-Large, Executive Board of Canadian Society of Biomechanics, 2000-
8. Member, Executive Board of the International Society of Biomechanics, 2003-

## PROFESSIONAL SERVICE

### Review Committees For Professional Meetings

1. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1989.
2. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1990.
3. Program Committee, combined meeting of the 9th International Symposium on Biomechanics in Sports and the Kinesiology Academy, June 29 - July 7, 1991.
4. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1991.
5. Review Panel Chair for Research Consortium, AAHPERD Convention, 1991-92.
6. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1992.
7. Review Panel Chair for Research Consortium, AAHPERD Convention, 1992-93.
8. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1993.
9. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1994.
10. Scientific Committee, International Society of Biomechanics in Sports Annual Meeting, Budapest, Hungary, June 1-6, 1994.
11. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1995.
12. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Madiera, Portugal, 1995-96.
13. Program Committee, New England American College of Sports Medicine Annual Meeting, Providence, RI, 1999.
14. Program Committee, New England American College of Sports Medicine Annual Meeting, Providence, RI, 2000.
15. Abstract Reviewer, XVIIIth Congress of the International Society of Biomechanics, ETH Zurich, Switzerland, July, 2001.
16. Abstract Reviewer, Vth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, July, 2001.
17. Member, Research Consortium Research Writing Award Committee, 2001.
18. Member, Holyoke Community College Department of Health and Fitness Advisory Board, 2001-
19. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Caceres, Spain, 2002.
20. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Beijing, China, 2003.

### External Reviewer for Theses and Dissertations

1. External Dissertation Reviewer, McMaster University, Hamilton, Ontario, Canada, June, 1995.
2. External Thesis Reviewer, Lakehead University, Thunder Bay, Ontario, Canada, June, 1995.

3. External Dissertation Reviewer, University of Guelph, Guelph, Ontario, Canada, January, 1997.
4. External Dissertation Reviewer, University of Connecticut, Storrs, Connecticut, December, 1998.
5. External Dissertation Reviewer, University of Delaware, Newark, Delaware, March, 2000.
6. External Thesis Reviewer, University of Delaware, Newark, Delaware, November, 2000.
7. External Dissertation Reviewer, University of Calgary, Calgary, Alberta, Canada, November, 2002.

#### **External Grant Reviewer**

1. External Reviewer for internal grants at University of Texas at Tyler, 1991.
2. Grant Reviewer, Natural Sciences and Engineering Council of Canada, 1993.
3. External Grant Reviewer, University Grants Committee, Hong Kong, February, 1998.
4. External Grant Reviewer, Natural Sciences and Engineering Council of Canada, May, 2000.
5. External Grant Reviewer, Canadian Institutes of Health Research, April, 2003.

#### **Committee Member**

1. Biomechanics Model Research Laboratory, Olympic Scientific Congress, University of Oregon, July, 1984.
2. Completed Research in Health, Physical Education, Recreation and Dance, 1986.
3. Research Consortium Program Review Committee, AAHPERD Annual Convention, April, 1987.
4. Kinesiology Academy, Nominating Board for Officers, 1987.
5. Completed Research in Health, Physical Education, Recreation and Dance, 1988.
6. Nominating Committee for Kinesiology Academy Chair, 1991.
7. Delegate to American Alliance Assembly, January 1, 1991 to December 31, 1991.
8. ASTM Committee F-8 on Sports Equipment and Facilities, June, 1992.
9. Conference Chair, International Society of Biomechanics in Sport Annual Meeting, University of Massachusetts Amherst, June 23-26, 1993.
10. Doctoral Program Evaluation Committee, American Academy of Kinesiology and Physical Education, 1997.
11. Program Review Committee for Biomechanics, Michigan State University, East Lansing, MI, January, 2000.
12. Continuing Committee for Doctoral Program Review, American Academy of Kinesiology and Physical Education, 2001-2002
13. Member, Research Consortium Research Writing Award Committee, 2001.
14. Member, AAHPERD Grant Proposal Committee, 2001.
15. Member, Holyoke Community College Department of Health and Fitness Advisory Board, 2001-

#### **EDITORIAL BOARD OF PROFESSIONAL JOURNALS**

Member, Editorial Review Board, *Pediatric Exercise Science*, 1988-

Member, Editorial Review Board, *Medicine, Exercise, Nutrition, and Health*, 1991-1995  
Guest Editor, Special Issue of *Pediatric Exercise Science*, The Physically Challenged Child, May, 1992.  
Section Editor, Biomechanics, *Research Quarterly for Exercise and Sport*, 1993-96  
Member, Editorial Review Board, *Journal of Applied Biomechanics*, 1996-1999  
Member, Editorial Board, *Research Quarterly for Exercise and Sport*, 1998-1999  
Associate Editor, *Medicine and Science in Sports and Exercise*, 2000-2002  
Member, Editorial Review Board, *Sports Biomechanics*, 2000-  
Member, Editorial Review Board, *Journal of Sports Sciences*, 2001-

#### AD HOC REVIEWER FOR PROFESSIONAL JOURNALS

Reviewer, *Medicine and Science in Sports and Exercise*, 1985-  
Reviewer, *International Journal of Sports Biomechanics*, 1986-  
Reviewer, *Research Quarterly for Exercise and Sport*, 1989-  
Reviewer, *Sports Medicine*, 1991-  
Reviewer, *Journal of Gerontology*, 1991-  
Reviewer, *Journal of Orthopedic and Sports Physical Therapy*, 1991-  
Reviewer, *Journal of Applied Biomechanics*, 1993-  
Reviewer, *Journal of Applied Physiology*, 1993-  
Reviewer, *Journal of Biomechanics*, 1993-  
Reviewer, *Clinical Journal of Sports Medicine*, 1996-  
Reviewer, *British Journal of Sports Medicine*, 1996-  
Reviewer, *Clinical Biomechanics*, 1999-  
Reviewer, *Exercise and Sports Science Review*, 2000-  
Reviewer, *European Journal of Applied Physiology*, 2000-  
Reviewer, *Journal of Rehabilitation Research and Development*, 2002-

#### PUBLICATIONS

Osternig, L. R., Sawhill, J. A., Bates, B. T., **Hamill, J.** A method for rapid collection and processing of isokinetic data. *Research Quarterly for Exercise and Sport* 53(3):252-257, 1982.

Knutzen, K. M., Bates, B. T., **Hamill, J.** Electrogoniometry of post surgical knee bracing in running. *American Journal of Physical Medicine* 62(4):172-181, 1983.

Osternig, L. R., **Hamill, J.**, Sawhill, J. A., Bates, B. T. Influence of torque and joint speed on power production. *American Journal of Physical Medicine* 62(4): 163-171, 1983.

**Hamill, J.**, Bates, B. T., Sawhill, J. A., Knutzen, K. M. Variations in ground reaction force parameters at different running speeds. *Human Movement Sciences* 2:47-56, 1983.

**Hamill, J.**, Bates, B. T., Knutzen, K. M. Ground reaction force symmetry during walking and running. *Research Quarterly for Exercise and Sport* 55(3):289-293, 1984.



Knutzen, K. M., Bates, B. T., **Hamill, J.** Knee brace influences on the tibial rotation and torque patterns of the surgical limb. *Journal of Orthopaedic and Sports Physical Therapy* 6(2):116-122, 1984.

Osternig, L. R., **Hamill, J.**, Corcos, D. M., Lander, J. E. Electromyographic patterns accompanying isokinetic exercise under varying speed and sequencing conditions. *American Journal of Physical Medicine* 63(6):289-297, 1984.

Knutzen, K. M., **Hamill, J.**, Bates, B. T. Ambulatory characteristics of the visually disabled. *Human Movement Sciences* 4:55-66, 1985.

Lander, J. E., Bates, B. T., Sawhill, J. A., **Hamill, J.** A comparison between free-weight and isokinetic bench pressing. *Medicine and Science in Sports and Exercise* 17(3): 344-353, 1985.

Smith, P. K., **Hamill, J.** The effect of punching glove type and skill level on momentum transfer. *Human Movement Studies* 12(3):153-161, 1986.

**Hamill, J.**, Knutzen, K. M., Bates, B. T., Kirkpatrick, G. M. Evaluation of two ankle appliances using ground reaction force data. *Journal of Orthopaedic and Sports Physical Therapy* 7(5):244-249, 1986.

Osternig, L. R., **Hamill, J.**, Lander, J. E., Robertson, R. Coactivation of sprinter and distance runner agonist/antagonist muscles in isokinetic exercise. *Medicine and Science in Sports and Exercise* 18(4):431-435, 1986.

**Hamill, J.**, Ricard, M. D., Golden, D. M. Angular momentum in multiple rotation non-twisting platform dives. *International Journal of Sport Biomechanics* 2(2): 78-87, 1986.

Knutzen, K. M., Bates, B. T., Schot, P., **Hamill, J.** Knee brace evaluation. *Medicine and Science in Sports and Exercise* 19(3):303-309, 1987.

**Hamill, J.**, Murphy, M. V., Sussman, D. H. The effects of track turns on lower extremity function. *International Journal of Sport Biomechanics* 3(3):276-286, 1987.

**Hamill, J.**, Morin, G., Clarkson, P. M., Andres, R. O. Exercise moderation of foot function during walking with a re-usable semirigid ankle orthosis. *Clinical Biomechanics* 3(3):153-158, 1988.

**Hamill, J.**, Bates, B. T. A kinetic evaluation of the effects of in vivo loading on running shoes. *Journal of Orthopaedic and Sports Physical Therapy* 10(2):47-53, 1988.

**Hamill, J.**, Freedson, P. S., Boda, W., Reichsman, F. Effects of shoe type and cardiorespiratory responses and rearfoot motion during treadmill running. *Medicine and Science in Sports and Exercise* 20(5):515-521, 1988.

Greer, N. L., **Hamill, J.**, Campbell, K. R. Ground reaction forces in children's gait. *Pediatric Exercise Science* 1(1):45-53, 1989.

**Hamill, J.**, Knutzen, K. M., Bates, B. T., Kirkpatrick, G. M. Relationship of static and dynamic measures of the lower extremity. *Clinical Biomechanics* 4(4):217-225, 1989.

Greer, N. L., **Hamill, J.**, Campbell, K. R. Dynamics of children's gait. *Human Movement Sciences* 8:465-480, 1989.

Brown, D. B., Knowlton, R. G., **Hamill, J.**, Schneider, T. L., Hetzler, R. K. Physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair ergometry. *European Journal of Applied Physiology* 60:179-182, 1990.

Holt, K. G., **Hamill, J.**, Andres, R. O. The force driven harmonic oscillator as a model for human locomotion. *Human Movement Science* 9:55-68, 1990.

**Hamill, J.**, McNiven, S. L. Reliability of ground reaction force parameters during walking. *Human Movement Science* 9:117-131, 1990.

Robertson, R. N., Osternig, L. R., **Hamill, J.**, DeVita, P. EMG-torque relationships during isokinetic dynamometer exercise. *Sports Training, Medicine and Rehabilitation* 2:1-10, 1990.

Holt, K. G., **Hamill, J.**, Andres, R. O. Predicting the minimal energy cost of human walking. *Medicine and Science in Sports and Exercise* 23(4):491-498, 1991.

**Hamill, J.**, Freedson, P. S., Clarkson, P. M., Braun, B. Muscle soreness during running: biomechanical and physiological implications. *International Journal of Sports Biomechanics* 7(2):125-137, 1991.

Devita, P., Hong, D. M., **Hamill, J.** Effects of asymmetric load carrying on the biomechanics of walking. *Journal of Biomechanics* 24(12):1119-1129, 1991.

Ebbeling, C. J., **Hamill, J.**, Freedson, P. S., Rowland, T. W. Efficiency in Children's Gait. *Pediatric Exercise Science*. 4(1):36-49, 1992.

Widrick, J., Freedson, P. S., **Hamill, J.** Effect of internal work on the calculation of optimal pedalling rates. *Medicine and Science in Sports and Exercise* 24(3): 376-382, 1992.

**Hamill, J.**, Bates, B. T., Holt, K. G. Timing of lower extremity joint actions during treadmill running. *Medicine and Science in Sports and Exercise* 24(7):807-813 1992.

Foti, T., Ebbeling, C. J., **Hamill, J.**, Ward, A., Rippe, J. Stair climbing machines: Lower extremity kinematics and exercise intensity comparisons. *Medicine, Exercise, Nutrition, and Health* 2:162-169, 1993.

Ebbeling, C. J., **Hamill, J.**, Crusemeyer, J. A. Lower extremity mechanics and the energy cost of walking in high-heeled shoes. *Journal of Orthopaedic and Sports Physical Therapy* 19 (4):190-196, 1994.

- Holt, K. G., Jeng, S. F., Ratcliffe, R., **Hamill, J.** Energetic cost and stability during human walking at the preferred stride frequency. *Journal of Motor Behavior* 27(2): 164-178, 1994.
- Hamill, J.**, Derrick, T. R., Holt, K. G. Shock attenuation and stride frequency during running. *Human Movement Science* 14:45-60, 1995.
- Whittlesey, S. N., **Hamill, J.** An alternative model of the lower extremity during locomotion. *Journal of Applied Biomechanics* 12(2):269-279, 1996.
- Jensen, R. L., Freedson, P. S., **Hamill, J.** The prediction of power and efficiency during near-maximal rowing. *European Journal of Applied Physiology* 73:98-104, 1996.
- Hamill, J.**, Caldwell, G. E., Derrick, T. R. Reconstructing digital signals using Shannon's Sampling Theorem. *Journal of Applied Biomechanics* 13:226-238, 1997.
- Mahar, A. T., Derrick, T. R., **Hamill, J.**, Caldwell, G. E. Impact shock and attenuation during in-line skating. *Medicine and Science in Sports and Exercise* 29(8):1069-1075, 1997.
- Derrick, T. R., **Hamill, J.**, Caldwell, G. E. Energy absorption in conditions of various stride frequencies. *Medicine and Science in Sports and Exercise* 30(1):128-135, 1998.
- Hamill, J.**, van Emmerik, R. E. A., Heiderscheit, B. C., Li, L. A dynamical systems approach to the investigation of lower extremity running injuries. *Clinical Biomechanics* 14(5):297-308, 1999.
- Li, L., Hardin, E. C., Caldwell, G. E., Van Emmerik, R. E. A., **Hamill, J.** Coordination patterns of walking and running at similar speed and stride frequency. *Human Movement Science* 18:67-85, 1999.
- Heiderscheit, B. C., **Hamill, J.**, Van Emmerik, R. E. A. Influence on Q-angle on the variability of lower extremity segment coordination during running. *Medicine and Science in Sport and Exercise* 31(9):1313-1319, 1999.
- Derrick, T. R., Caldwell, G. E., **Hamill, J.** Modeling the stiffness characteristics of the human body while running at various stride frequencies. *Journal of Applied Biomechanics* 16:36-51, 2000.
- Heiderscheit, B. C., **Hamill, J.**, Caldwell, G. E. Influence on Q-angle on lower extremity kinematics during running. *Journal of Orthopedic and Sports Physical Therapy*, 30(5):271-278, 2000.
- McCaw, S. T., Heil, M. E., **Hamill, J.** The effect of comments about shoe construction on impact forces during walking. *Medicine and Science in Sport and Exercise* 32(7):1258-1264, 2000.
- Whittlesey, S. N., Van Emerik, R. E. A., **Hamill, J.** The swing phase of human walking is not a passive movement. *Motor Control*, 4(3):273-292 2000.

**Hamill, J.**, Haddad, J.M., McDermott, W.J. Issues in quantifying variability from a dynamical systems perspective. *Journal of Applied Biomechanics*, 16:409-420, 2000.

Williams, D. S., McClay, I. S., **Hamill, J.**, Buchanan, T. S. Lower extremity kinematic and kinetic differences in runners. *Journal of Applied Biomechanics* 17:153-163, 2001.

Williams, D. S., McClay, I. S., **Hamill, J.** Arch structure and injury patterns in runners. *Clinical Biomechanics* 16(4):341-347, 2001

O'Connor, K. M., **Hamill, J.** Does running on a cambered road predispose a runner to injury? *Journal of Applied Biomechanics* 18(1):3-14, 2002.

Heiderscheit, B. C., **Hamill, J.**, Van Emmerik, R. E. A. Locomotion variability and patellofemoral pain. *Journal of Applied Biomechanics* 18(2):110-121, 2002.

Hardin, E. C., **Hamill, J.** The influence of midsole cushioning on mechanical and hematological responses during a prolonged downhill run. *Research Quarterly for Exercise and Sport* 73(2):125-133, 2002.

Li, L., **Hamill, J.** Characteristics of the vertical ground reaction force component prior to gait transition. *Research Quarterly for Exercise and Sport* 73(3):229-237, 2002.

Mercer, J. A., Vance, J., Hreljac, A., **Hamill, J.** Relationship between shock attenuation and stride length during running at different velocities. *European Journal of Applied Physiology* 87:403-408, 2002.

Peters, B. T., Haddad, J. M., Heiderscheit, B. C., Van Emmerik, R. E. A., **Hamill, J.** Limitations in the use and interpretation of continuous relative phase. *Journal of Biomechanics* 36:271-274, 2003.

Laughton, C. A., McClay, I. S., **Hamill, J.** Effect of strike pattern and orthotic intervention on tibial acceleration during running. *Journal of Applied Biomechanics* 19(2):153-168, 2003.

McDermott, W. J., Van Emmerik, R. E. A., **Hamill, J.** Running training and adaptive strategies of locomotor/respiratory coordination. *Journal of Applied Physiology* 89:453-444, 2003.

Hardin, E. C., **Hamill, J.** Kinematic adaptations during running: footwear, surface and duration consequences. *Medicine and Science in Sports and Exercise*, (In press).

### **MANUSCRIPTS UNDER REVIEW**

Hardin, E., **Hamill, J.** The influence of shoe/surface interactions on impact shock attenuation. *Journal of Sports Science*, 2003.

O'Connor, K., **Hamill, J.** The role of extrinsic foot muscles during running. *Clinical Biomechanics*, 2003.

O'Connor, K., **Hamill, J.** Frontal plane kinetics may not reflect foot function. *Journal of Applied Biomechanics*, 2003.

## MANUSCRIPTS IN PREPARATION

Derrick, T. R., Caldwell, G. E., Hamill, J. The effect of simulated MUAP shape, rate and variability on the power spectrum.

Hamill, J., Derrick, T. R. Co-contraction of lower extremity muscles under varying stride frequency conditions.

Hamill, J., Derrick, T.R., McClay, I. Joint stiffness during running with different footfall patterns.

## PROCEEDINGS

Bates, B. T., Sawhill, J. A., **Hamill, J.** Dynamic running shoe evaluation. In Proceedings of Human Locomotion, Special Conference of the Canadian Society of Biomechanics, 122-124, London, Ontario, October, 1980.

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### **International:**

Holt, K. G., **Hamill, J.**, Certo, C., Fitzgerald, M. Tuning the novice runner to resonance. Xth Meeting of the International Society for Biomechanics in Sports, Milan, Italy, June, 1992.

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O'Connor, K., Price, T., **Hamill, J.** Muscle activation levels running in varus, valgus and neutral wedged shoes. IVth World Congress of Biomechanics, Calgary, Canada, August, 2002.

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Sussman, D. H., **Hamill, J.** Effect of high and low top basketball shoes on sub-talar pronation. American Alliance for Health, Physical Education, Recreation and Dance Annual Meeting, Cincinnati, OH, April, 1986.

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Holt, K. G., Jeng, S. F., Ratcliffe, R., **Hamill, J.** Optimality criteria in walking. Tenth Annual Meeting, International Society for Ecological Psychology, Hartford, CT, October, 1991.

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Holt, K. G., Jeng, S. F., Ratcliffe, R., **Hamill, J.** Exploring the use of non-linear dynamics in the assessment of stability of human walking. 13th Annual Conference IEEE, Engineering in Medicine and Biology, Orlando, FL, November, 1991.

Holt, K. G., Jeng, S. F., Ratcliffe, R., Thompson, S., **Hamill, J.** Stability and the metabolic cost of human walking. XIth International Symposium on Posture and Gait: Control Mechanisms, Portland, OR, May, 1992.

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Li, L., Heiderscheit, B. C., Caldwell, G. E., **Hamill, J.** Knee joint stiffness during the stance phase of level running. Annual Meeting of the Combined Sections of the American Physical Therapy Association, Boston, MA, February, 1998.

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Haddad, J., van Emmerik, R. E. A., Whittelsey, S.N., **Hamill, J.** Inter- and intra-limb coordination under asymmetrical loading. American Alliance for Health, Physical Education, Recreation and Dance Annual Meeting, Orlando, FL, March, 2000.

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**Regional, State, and Local:**

**Hamill, J.** A comparison of selected kinematic parameters in the support phase of running on various inclinations. Conference of the Oregon Alliance for Health, Physical Education, Recreation and Dance, October, 1980.

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**Hamill, J.,** Bates, B. T. Effects of shoe-orthotic interactions. New England Chapter of the American College of Sports Medicine Annual Meeting, Foxboro, MA, November, 1986.

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Ebbeling, C. J., **Hamill, J.,** Foti, T., Ward, A., Rippe, J. Kinematics of the lower extremity on stair-stepping machines. New England Chapter of the American College of Sports Medicine Annual Meeting, Marlborough, MA, November, 1990.

Hintermeister, R. A., **Hamill, J.** Is symmetry valid in running? New England Chapter of the American College of Sports Medicine Annual Meeting, Marlborough, MA, November, 1990.

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Elliott, E. H., **Hamill, J.,** Derrick, T. R. Reliability of the LiftStation measurement system. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1993.

Derrick, T. R., **Hamill, J.,** Foti, T. Spectral analysis of EMG during running in orthotic/non-orthotic conditions. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1993.

Elliott, E. H., **Hamill, J.,** Derrick, T. R. The influence of multiple lifts on load kinematics in males and females. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1994.

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Hardin, E. C., **Hamill, J.**, Taylor, J. M. The influence of midsole durometer on leg shock, hemocrit and muscle damage during downhill running. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1995.

Heiderscheit, B. C., **Hamill, J.**, Derrick, T. R. Relationship between Q-angle and lower extremity kinematics during running. Annual Conference of the Massachusetts Chapter of the APTA, Danvers, MA, October, 1996.

Busconi, K., Gore, M., **Hamill, J.**, Freedson, P. Time motion profile of U. S. Olympic field hockey players during game conditions. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1996.

Heiderscheit, B. C., **Hamill, J.**, Derrick, T. R. Relationships between Q-angle and lower extremity kinematics. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1996.

Goff, D., **Hamill J.**, Clarkson, P. Biomechanical and biochemical changes after downhill running. New England Chapter of the American College of Sports Medicine Annual Meeting, Providence, RI, September, 1997.

## KEYNOTE PRESENTATIONS

Mechanics of tower dive take-offs. United States Diving Association Annual Convention, Phoenix, AR, September, 1985.

Mechanics of walking. National Prescription Footwear Association, New York, NY, November, 1987.

Athletic Footwear and Injury. American Public Health Annual Meeting, Boston, Massachusetts, November 15, 1988.

Biomechanics of the lower extremity. Southeast Chapter of the American College of Sports Medicine Annual Meeting, Louisville, Kentucky, February 2, 1991.

Timing of lower extremity joint actions: A mechanism for knee injury? Northwest Chapter of the American College of Sports Medicine Annual Meeting, Eugene, OR, February 11, 1993.

Running injuries and rehabilitation. International Society of Biomechanics in Sports Annual Meeting, Budapest, Hungary, June 5, 1994.

Biomechanical aspects of children during exercise. IXth Annual NASPEM Conference, Pittsburg, PA, August 12, 1994.

Evaluation of athletic footwear using ground reaction force data. International Society of Biomechanics in Sports Annual Meeting, Madiera, Portugal, June, 1996.

Biomechanics of distance running. International Symposium of the Research Institute of Sports Science at Korean National University, Seoul, Korea, October 17, 1997.

Evaluation of shock attenuation. Fourth Symposium of the Technical Group on Footwear Biomechanics, Canmore, Alberta, Canada, August 6, 1999.

Segment coupling and running injuries. University of Nevada-Las Vegas Distinguished Lecture Series, Las Vegas, Nevada, March 1, 2002.

Role of variability in the etiology of lower extremity running injuries. International Symposium of the Research Institute of Sports Science at Korean National University, Seoul, Korea, October 25, 2002.

## **INVITED PRESENTATIONS**

Effects of running shoes on foot function. Y.M.C.A., Eugene, OR, October, 1981.

Medio-lateral foot function during locomotion. University of Illinois Graduate Faculty and students, Champaign, IL, February, 1983.

Biomechanics of walking. American Heart Association Walk for Life, St. Louis, MO, May, 1987.

Biomechanics of walking and running shoes. New Mexico Race Walkers Association, Albuquerque, New Mexico, June, 1987.

Biomechanics of fitness walking. American Diabetes Association, St. Louis, Missouri, September, 1987.

Orthotics and lower extremity function. Athletic Training Symposium, American Alliance for Health, Physical Education, Recreation and Dance Annual Meeting, Kansas City, Missouri, April, 1988.

Running analysis from both a biomechanical and physiological perspective. Symposium, New England College of Sports Medicine Annual Meeting, Worcester, MA, November 4, 1988.



If the shoe fits: A biomechanical analysis of locomotion. Sigma Xi Society, University of Massachusetts, Amherst, MA, November 16, 1988.

Muscle soreness during running: Biomechanical and physiological considerations. Neuromuscular Research Center Seminar, Boston University, September 20, 1989.

Design of athletic shoes : Biomechanical considerations. Kinesiology Academy Meeting at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, New Orleans, LA, April 28, 1990.

Biomechanical implications of the design of running shoes. Physical Therapy Department, Boston University, April 18, 1990.

Biomechanics of running. Physical Therapy Department, Boston University, November 6, 1990.

Is biomechanics an atheoretical discipline? Kinesiology Academy Teaching Conference, Ames, Iowa, July 5, 1991.

Biomechanics of Running. Education Resources Inc. Conference, Framingham, MA, September 27, 1991.

Optimality criteria for human locomotion. Motor Control/Biomechanics Seminar, Department of Exercise and Human Movement Studies, University of Oregon, January, 1992.

Biomechanical considerations for equipment design in children's sports. Seminar on Children's Activities, United Hospital Medical Center, Port Chester, NY, March 28, 1992.

Efficiency of children's gait. (with C. J. Ebbeling). Kinesiology Academy Symposium at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, Indianapolis, IN, April 13, 1992.

Optimality criteria for human locomotion. (with K. G. Holt and A.F. Maliszewski). Symposium at the American College of Sports Medicine Annual Meeting, Seattle, Washington, June 5, 1993.

The influence of step aerobics on knee angle. Research Symposium at the IDEA Annual Conference, New Orleans, Louisiana, June 21, 1993.

Rearfoot motion in running. (with K. G. Holt and C. J. Edington). Symposium at the New England College of Sports Medicine Annual Meeting, Boxborough, MA, November 5, 1993.

Controversies in the calculation of mechanical energy. (with K. D. Browder and L. Darby). Biomechanics Academy Symposium at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, Denver, CO, April 13, 1994.

Stability and rearfoot motion testing: A proposed standard. (with M. Milliron and J. Healy). VIIIth Biennial Meeting of the Canadian Society for Biomechanics, Calgary, Canada, August, 1994.

Stride Frequency and Foot Strike Impact. Dept. of Exercise and Sports Science. Arizona State University, December 8, 1994.

Biomechanics of functional footwear. (with M. Shorten). Pre-Conference Symposium at the International Society of Biomechanics Biannual Meeting, Jyvaskyla, Finland, June, 1995.

Impact shock attenuation during conditions of altered stride frequencies in running. (with T. R. Derrick and K. G. Holt). Biomedical Engineering Society Meeting, Boston, MA, October, 1995.

Shoe and surface influences on ACL injuries. (with B. Busconi). American Volleyball Coaches Annual Meeting, Springfield, MA, December 15, 1995.

A force-driven harmonic oscillator model of human locomotion. German Sports University, Cologne, Germany, February 29, 1996.

If the shoe fits: the biomechanics of running shoes. American Medical Athletic Association, Boston, MA, April 12, 1996.

Biomechanics of athletic footwear. (with Martyn Shorten). American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, Atlanta, GA, April, 1996.

An oscillator model of locomotion. University of Massachusetts Physics Department Seminar, Amherst, MA, May 1, 1996.

The mechanics of orthotics. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November 7, 1996.

A case study of a patient with patellofemoral pain. Eugene Michaels Lecture at the Combined Sections Meeting of the American Physical Therapy Association Annual Meeting, Dallas, Texas, February 14, 1997.

Oscillator Models of Human Locomotion. Korean Sports Science Institute, Seoul, Korea, October 15, 1997.

Lower extremity variability during running. Physical Therapy Department Seminar, University of Delaware, February 20, 1998.

Shock attenuation and transmission during running. (with T. R. Derrick). XVIIth Congress of the International Society of Biomechanics, Calgary, Alberta, Canada, August 12, 1999.

Variability and Stability: A Dynamical Systems Perspective. (with Van Emmerik, R. E. A., Heiderscheit, B., Li, L). Invited Symposium at the Annual Meeting of the American College of Sports Medicine, Indianapolis, IN, June, 2000.

From a Pendulum to a Spring. Department of Kinesiology, Louisiana State University, Baton Rouge, LA, October 24, 2000.

Oscillators and Springs. The Gladys Garrett Honor Lecture, Department of Exercise Science, University of Connecticut, Storrs, CT, May, 2001.

Joint Coupling variability and knee pain during running. (with B. Heiderscheit, R. Van Emmerik, J. Haddad). XVIIIth Congress of the International Society of Biomechanics, ETH Zurich, Switzerland, July, 2001.

Current Issues in Biomechanics. Beijing University, China, October 16, 2001.

Mechanical models and human locomotion. Beijing University, China, October 18, 2001.

A primer in 3-D: Considerations for biomechanical research. University of Las Vegas-Nevada, Las Vegas, Nevada, February 28, 2002.

Tibial stress fractures: A prospective study. Human Performance Laboratory, University of Calgary, Calgary, Alberta, Canada, November 29, 2002.

## **EXTERNAL FUNDING**

### **Grants**

1. Dynamics of platform diving, United States Diving Association, \$3,000, 1/1984 - 12/1984. 9/1985 - 6/1986.
2. Effects of anatomically variant foot-types on walking gait, ORDA, Southern Illinois University, \$6,000,
3. Effect of orthotic inserts on walkers with rearfoot and forefoot dysfunctions. Biomedical Research Support Grant, University of Massachusetts, \$6,000, 1/1987 - 1/1989.
4. Activity in later life: effects on posture and gait. National Institute of Aging, co-principal investigator, resubmitted January 28, 1988 (approved but not funded).
5. Musculoskeletal fitness norms for individuals aged 45-75. National Institute of Health, submitted February 1, 1988 (approved but not funded).
6. Mechanics of springboard diving: Modeling the diver-board system, United States Diving Association, \$15,000, 1/1989 - 1/1991.
7. Biomechanical analysis of military boots, (Grant #DAAK60-91-C-0102) U.S. Army, Natick, MA, \$183,000, 7/1991 - 12/1992.

8. Biomechanical analysis of military boots, (Grant #DAAK60-95-R-8010) U.S. Army, Natick, MA, (with Wellco Industries, North Carolina), \$51,436, 9/1995 - 12/1997.

9. Biomechanical analysis of military boots: Phase III, (Grant #DAAK60-95-R-8010) U.S. Army, Natick, MA, (with Wellco Industries, North Carolina), \$5,000, 9/1999 - 12/1999.

10. Biomechanical analysis of military boots. (Contract #DAAK16-00-P-0112) U.S. Army Soldier Systems Center, Natick, MA, \$25,000, 1/2000 - 6/2000.

11. Prospective study on tibial stress fractures. (Grant # DAMD17-00-1-0515), Department of the Army, (with Irene McClay). \$1,050,000, 8/1/2000 - 8/1/2004.

### **Contracts**

1. Mechanics of lower extremity function, Isotechnologies, Inc., \$12,000, 9/1982 - 6/1984.

2. Ergonomics of lower extremity function, KangaROOS, USA, \$58,000, 9/1986 - 9/1989.

3. Prophylactic Knee and Ankle Bracing, AirCast Corp., \$20,000, 9/1988 - 9/1989.

4. Lower extremity action during exercise, Life-Fitness Group, \$6,000, 7/1990 - 7/1992.

5. Lower extremity mechanics, Hyde Athletic Shoe Company, \$279,000, 1/1989 - 1/1997.

6. Biomechanical analysis of golf equipment, Titleist and FootJoy Worldwide, \$283,000, 6/1992-12/1997.

7. Biomechanical analysis of hiking gait, The Timberland Company, \$15,000, 3/1995 - 10/1995.

8. A physiological profile of the game of field hockey. (with P. S. Freedson). United States Olympic Committee, Colorado Springs, Colorado, \$35,132, 1/1996 - 12/1996.

9. Locomotor patterns on running machines. NordicTrak, \$10,000, 9/1997-3/1998.

10. Plantar pressure patterns during hiking gait. The Timberland Company, \$42,000, 3/1998 - 5/1999

11. Investigation of foot scaling using a 3-D laser measurement system. Titleist and FootJoy Worldwide, \$50,000, 1/1999 - 12/2000

12. Biomechanical analysis of golf footwear, Titleist and FootJoy Worldwide, \$63,000, 1/1999-12/1999.

13. Walking and running mechanics and their effect on footwear, Hyde Athletic Shoe Company, \$33,000, 1/1999 - 12/1999.

14. In-shoe temperatures during hiking, The Timberland Company, \$15,000, 1/1999-3/1999.
15. Plantar forces during basketball movements, And1 Company, \$15,000, 1/1999-3/1999.
16. Rearfoot motion and shock attenuation in trial running footwear, The Timberland Company, \$10,000, 6/1999-7/1999.
17. Running mechanics and their effect on footwear. Hyde Athletic Shoe Company, \$33,000, 1/2000 - 12/2000.
18. Implementation of a 3-D laser measurement system. Titleist and FootJoy Worldwide, \$89,000, 1/2000 - 12/2000.
19. Shock attenuation in hiking footwear. The Timberland Company, \$18,000, 1/2000 - 6/2000.
20. Traction analysis of golf footwear. Titleist and FootJoy Worldwide, \$48,000, 1/2000 - 12/2000.
22. Footwear Testing. Titleist and FootJoy Worldwide. \$50,000, 1/2001 - 12/2001.
23. 3-D laser measurement system. Titleist and FootJoy Worldwide, \$89,000, 1/2001 - 12/2001.
24. Walking mechanics and their effect on footwear. Hyde Athletic Shoe Company, \$33,000, 1/2001 - 12/2001.
25. Modeling Parachute Landing Falls. Sub-contract from Foster-Miller, Inc., Waltham, MA, \$85,000, 1/2001 - 8/2003.
26. A new 3-D laser measurement system. Titleist and FootJoy Worldwide, \$69,000, 1/2002 - 12/2002.
27. Footwear Testing. Titleist and FootJoy Worldwide, \$50,000, 1/2002 - 12/2002.
28. Footwear Testing. Hyde Athletic Shoe Company, \$16,500, 1/2002 - 6/2002.
29. Footwear Testing, Timberland Company, \$24,000, 1/2002 - 12/2002.
30. Footwear Testing. Titleist and FootJoy Worldwide, \$124,000, 1/2003 - 12/2003.
31. Footwear Testing, Timberland Company, \$24,000, 1/2003 - 12/2003.